

PROTOTYPES FOR HUMANITY

2025

SHORT PAPERS PLATFORM
CONFERENCE PROCEEDINGS

ISBN: 9789948612100

First Edition

Prototypes for Humanity

2025

**Short Papers Platform Conference
Proceedings**

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Published: June 2026

DOI: 10.18502/rq457c78

ISBN-eBook: 9789948612100

ISBN-Print: 9789948613978

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About Prototypes for Humanity

Prototypes for Humanity is a global platform dedicated to bridging the gap between academic research and real-world implementation. Founded in 2014 as a showcase of graduate projects contributing to a better planet, it has grown into a leading platform for academic innovation, drawing on a community of professors, graduates and students across all disciplines, from over 1,200 universities in 130 countries. Prototypes for Humanity is owned and managed by the Art Dubai Group.

Through its showcase and forums, prizes, venture development and funding programme, knowledge dissemination platforms and partnership frameworks, Prototypes for Humanity enables tangible collaborations between academics and key stakeholders from the global innovation community — to solve pressing challenges, structure market-driven ventures and support socio-economic progress.

The programme's flagship annual convening, the Dubai Future Solutions - Prototypes for Humanity summit, is delivered in strategic collaboration with the Dubai Future Foundation, offering global promotion, industry pilot and funding opportunities, awards and collaboration pathways to academics from around the world.

Prototypes for Humanity is held under the patronage of Her Highness Sheikha Latifa bint Mohammed bin Rashid Al Maktoum, Chairperson of Dubai Culture and Arts Authority (Dubai Culture).

For more information, visit www.prototypesforhumanity.com

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Foreword from the Organisation

Prototypes for Humanity is a global programme that accelerates the translation of academic research into applied solutions with tangible impact. We work hands-on with academics from across 1200 universities in 130 countries to bridge the gap between scientific discovery and real-world application, and connect that knowledge with the people, communities, places, and industries that need it most.

Historically, academic research has been critical to solving complex challenges and driving economic and social growth since the inception of the first universities. For that engine to work, however, there needs to be a deliberate and concerted effort towards research application, translation, and implementation. That was the north star of the 2025 Short Papers Platform, engaging academics from around the world whose work addresses pressing issues and responds to pragmatic industry, user and public requirements, in alignment with Dubai's forward-looking priorities—a vision the Dubai Future Foundation has been instrumental in enabling through its strategic support of our wider programme.

I am delighted to present the inaugural issue of our official publication, marking a significant milestone for the programme. A deliberate exercise in multi-disciplinary research, this edition highlights critical themes ranging from infrastructure resilience and sustainability to health, mobility, and the digital economy. These 56 short papers reflect a broad spectrum of contemporary inquiry and the urgency of the issues they address. Beyond their academic rigour, these contributions respond directly to challenges currently facing public and private organisations—a testament to the power of academic expertise when applied to live problems.

Prototypes for Humanity will continue to create the conditions for innovation to move beyond the laboratory and into practice. Through the Short Papers platform and our wider programme, we remain committed to amplifying the work of professors, graduates, and students whose research has the potential to drive meaningful change, and to strengthening the connections with industry and the public sector that make that journey possible.

I extend my sincere appreciation to the authors, reviewers, stakeholders, and our team, whose contributions have made this publication possible. The ideas gathered in this volume represent the beginning of a journey we support wholeheartedly.

Tadeu Baldani Caravieri

Managing Director, Prototypes for Humanity

Prototypes for Humanity 2025: The Short Papers

Naren Barfield, Editor-in-Chief

Prototypes for Humanity's expansion in 2025 into short papers, pecha kuchas and innovation sandpits marks a deliberate development in how academic research is convened. The aim is simple: to create a platform where serious researchers can interrogate real-world problems with clarity, rigour and imagination, and where ideas and outcomes can be tested, challenged and strengthened through contact with other fields. The premise is straightforward. Universities across the world generate extraordinary research, but much of it remains siloed, slow to circulate, or locked within disciplinary conventions that do not match the complexity of the challenges we face. The inaugural short papers platform provides a common format through which researchers from diverse disciplines can communicate insights quickly and precisely, while also providing a shared space in which problems can be examined and collaborations formed before solutions are attempted.

Across this year's submissions, a convergence of fields is visible. This is not interdisciplinarity as a requirement imposed on contributors, but an observed pattern: when researchers gather around shared challenges rather than disciplinary categories, new lines of inquiry open up. Problems are reframed, assumptions are questioned, and mechanisms that might remain invisible within a single field are revealed. Research across multiple domains show that when specialists work together, they tend to surface underlying drivers that single-discipline approaches might miss, and generate solutions that are both more innovative and more grounded in real-world contexts. The short papers platform is designed to make this possible: not by forcing interdisciplinarity, but by creating the conditions in which it can emerge naturally.

The thematic structure reflects this intention. The seven themes: **Wellbeing and Health Futures; Sustainable and Resilient Infrastructure; Artificial Intelligence and Augmented Intelligence; Environmental Sustainability and Climate Action; Socio-Economic Empowerment and Innovation; Open; and Speculative**, are not categories of research. They are problem-spaces: areas where global pressures, technological change and societal expectations intersect, and where new knowledge is urgently needed. Each theme is broad enough to accommodate diverse methods and perspectives, yet specific enough to anchor the work in recognisable global priorities.

At best, the themes capture work that sits ahead of established fields, or that does not yet fit comfortably within existing academic or industrial frameworks. These themes act as discovery engines, ensuring that the programme remains receptive to emerging ideas, unfamiliar methods and early-stage insights that may later crystallise into new areas of research, innovation, or practice.

The selection process for the chapters presented in this volume was organised around three criteria: *insight*, *innovation* and *impact*. They are the criteria used to judge the submissions: the clarity with which a problem is identified or understood; the originality of the approach; and the potential for real-world benefit. They are neutral with respect to discipline and output type, and they align with the

programme's commitment to problem discovery, methodological diversity and solution-making. Their purpose is practical: to identify work that advances understanding and has the potential to shape futures in tangible and beneficial ways.

Taken together, the short papers format, the thematic structure and the evaluative criteria form a coherent architecture. It is inclusive across fields, aligned with global and local priorities, and designed to surface research that is both academically robust and capable of informing action. The aim is not to produce a catalogue of academic achievements, but to create a body of work that can be revisited, extended and recombined over time—a cumulative resource for researchers, policymakers, industry partners, and communities who are grappling with the same challenges from different vantage points.

The papers that follow demonstrate the value of this approach. They show how researchers from across the world are addressing problems that cut across health, infrastructure, climate, technology, and social systems. Collectively, they reveal patterns, tensions, and opportunities that no single field would be likely to identify alone, and they illustrate how academic work, when brought into contact with other perspectives, can generate insights that are both rigorous and actionable. This is the purpose of the short papers platform: to convene serious research, to create the conditions for collaboration, and to support the development of insight, innovation, and impact in ways that improve lives.

The contributors to the 2025 short papers platform form a genuinely global cohort. Authors and co-authors span multiple regions and research cultures, reflecting the reality that the challenges addressed across the seven themes are shared internationally, while informed by different social, environmental, and technological contexts.

Institutional diversity is equally marked. The short papers originate from research-intensive universities, specialist institutes, design schools, engineering faculties, medical schools, and applied research centres, alongside collaborations with industry partners, NGOs, communities, and public-sector organisations. This range demonstrates that the platform draws from a full research ecosystem. Single-authored papers are rare; most submissions are co-authored, and many involve teams spanning multiple departments, universities, or sectors. Several chapters emerge from academia-industry collaborations in problem definition, prototype testing, or real-world deployment. These partnerships shape research questions and methods; they are integral to the work, not peripheral.

The disciplinary spread is wide and intentional. The papers draw on engineering, medicine, public health, AI and data science, architecture, design, environmental science, economics, social policy, materials science, and speculative design. Many sit at, or across, the boundaries between fields, reflecting the platform's emphasis on the interstices of knowledge, where new mechanisms, overlooked approaches, and alternative framings emerge.

This diversity is deliberate and productive. Global challenges may be shared, but their drivers and interventions differ across contexts. A contributor base that spans continents, institutions, and sectors ensure that insights and proposed solutions are informed by multiple realities. It also strengthens engagement, ownership, and legitimacy for researchers, stakeholders, and the public.

In this configuration, the short papers platform operates as a global knowledge common: a space where disciplinary excellence, geographic breadth, and collaborative intent combine to generate insights. The papers that follow show this convening power at its clearest.

Wellbeing and Health Futures considers how societies understand, protect, and extend human wellbeing in an era shaped by demographic change, environmental pressures, and rapid technological development, encompassing the full spectrum of health, from prevention and early detection to treatment, recovery, and long-term care, while recognising that wellbeing is influenced as much by social conditions and environmental exposures as by clinical interventions. The theme brings together work on healthy ageing, maternal and child health, mental health, digital and precision medicine, public health policy, environmental determinants of disease and the design of products, materials, and systems that support healthier lives. As a body of work, it invites reflection on how health systems might evolve, how inequities can be reduced, and how new technologies can be harnessed responsibly to improve quality of life.

Plasma polymerised nanoparticles: from cell imaging to cancer therapy by Behnam Akhavan and colleagues develops plasma polymerised nanoparticles (PPNs) as a solvent-free, radical-rich nanopatform that enables stable, linker-free conjugation of dyes and anticancer drugs. By unifying imaging and therapy within a single construct, it contributes to the theme's concern with integrated diagnostic-therapeutic systems that can simplify and strengthen cancer care pathways.

Amin Al-Habaibeh and colleagues' paper **Affordable Brainwave Reader to Help people with Motor Neurone Disease (MND) Communicate via Thoughts Using Novel AI Technology** presents a low-cost EEG-based brain-computer interface that uses novel AI methods to classify two mental imagery states for basic communication in people with MND and CLIS. It reframes assistive communication as a problem of affordability and accessibility rather than of high-end laboratory technology, with low-cost deployment potential.

Multimodal Platform for Objective Pain Measurement, by Yacine Hadjiat and colleagues develops an AI-powered multimodal Pain Index that integrates wearable biosignals to quantify pain objectively in real time, addressing a long-standing clinical gap: the absence of reliable pain assessment tools for patients who cannot self-report. Their work demonstrates insight into autonomic biomarkers, coupled with impact through a scalable clinical decision tool for diverse patient populations.

The research of Basri Abdullah and colleagues is presented in **Equira™ (VoxelPHITS): Democratising Precision Radiopharmaceutical Therapy for Global Cancer Care**, which converts routine CT/SPECT/PET imaging into patient-specific 3D dose maps using Monte Carlo kernels, enabling personalised radionuclide therapy without specialised dosimetry infrastructure, showing how precision radiopharmaceutical therapy can be extended beyond high-resource centres, bringing potential widening global access to precision cancer care.

Ernest Kamavuako's research introduces a compact multimodal device that captures ECG, EMG, and heart sounds with AI-based interpretation, validated against gold-standard cardiac systems. **A low-cost, portable and AI-powered device for cardiac investigation** targets early cardiac investigation in low-

and middle-income settings through integrated sensing rather than fragmented diagnostics, delivering impact through affordability and innovation in unified biosignal acquisition for frontline cardiac assessment.

Michele Magno and colleagues' **Edge AI-Enabled Smart Glasses and Companion Robots for In-Home Health Monitoring and Medication Adherence** integrates radar-based vital-sign sensing, hybrid EOG eye-tracking, and gaze-guided quadruped robots into a low-power ecosystem for in-home health monitoring and medication adherence, reframing ageing-in-place and chronic-disease management as problems of continuous, unobtrusive monitoring rather than episodic clinical contact.

Patricia Maguire and colleagues' chapter, **Transforming Preeclampsia Care Through Cross-Disciplinary Innovation: From Platelet Biomarkers to Real-Time Clinical Decision Support**, presents AI_PREMie, which combines platelet-derived biomarker panels with machine-learning models to support diagnosis, severity assessment, and delivery-timing decisions in suspected preeclampsia. It shows how molecular insight and computational modelling can jointly address a high-risk maternal condition with substantial global morbidity and mortality.

MONA: A Robotic Patient Simulator for Occupational Therapists Training by Perla Maiolino and colleagues describes a full-body robotic patient simulator equipped with 4,000 tactile sensors, motorised joints, and adaptive pain responses to support realistic occupational therapy training in mobility and touch-based assessment. It addresses workforce preparedness and the need for high-fidelity, repeatable training environments in rehabilitation and care for an ageing population.

Anthony McGarry's **PCAD: Prosthetic Comfort by Design An Educational Innovation in Prosthetic Measurement** combines pressure-based loaded limb capture with automated CAD scanning to produce accurate, modification-free prosthetic sockets within seconds, reducing clinical time and remakes. It reframes prosthetic provision as a workflow-efficiency and precision-fit challenge rather than a purely artisanal process, contributing to global accessibility, consistency, and training in prosthetic care.

Eleonora Secchi and colleagues present **PermeaSense: Rethinking how we test antimicrobials in the fight against biofilm infections** which cultivates biofilms on engineered membranes and quantifies antimicrobial penetration and matrix disruption in real time, generating spatial susceptibility profiles. It addresses the methodological gap between early-stage antimicrobial discovery and clinically relevant evaluation in biofilm-associated infections.

Nanoplants (Nanostructured Implants) by Bala Vaidhyanathan and colleagues develops nanostructured zirconia-based implants using additive manufacturing and microwave sintering to achieve exceptional hydrothermal ageing resistance and near-net-shape fabrication, linking advanced materials engineering with long-term implant durability and cost-efficient production in dental and orthopaedic applications.

Deisy Yurley Rodríguez-Sarmiento introduces **Artificial Intelligence and Quantum Computing for the Design of Novel Kisspeptin-10 Analogues and Their Experimental Evaluation in Cervical Cancer Cells**, where AI-driven peptide design and quantum-assisted docking are used to generate

Kisspeptin-10 analogues with enhanced Kiss1R affinity, followed by experimental validation of cytotoxicity and migration inhibition in cervical cancer cells. The research demonstrates how computational acceleration can reshape early-stage oncology drug discovery while remaining anchored in wet-lab evaluation.

The **Sustainable and Resilient Infrastructure** theme examines how infrastructure can be conceived, built and maintained in ways that support long-term environmental, social and economic resilience, spanning the design of buildings, transport, energy and water systems, as well as the materials, technologies and manufacturing pipelines that underpin them. The theme addresses climate-resilient planning, sustainable construction, mobility futures, occupational safety, air quality, waste reduction and the improvement of essential services for underserved communities. Drawing together engineering, architecture, urban design, environmental science, digital technologies and public policy, this theme recognises the need for integrated approaches that create environments capable of withstanding future shocks while improving everyday life.

Andrea Conserva and colleagues explore how AI and digital twins can be used to co-create cities in **Co-Creating Cities with AI and Digital twins: a multi-species participatory approach**. It positions urban infrastructure as something shaped not only by human stakeholders but by the wider ecological systems with which cities interact, providing insight into participatory and ecological urbanism, combining AI and digital twins with multispecies perspectives, and potential impact on how future cities are planned and governed.

ThermoChroma-smart colorimetric sensors as cold chain indicators by Ahu Gümrah Dumanli presents ThermoChroma-smart colorimetric sensors designed to act as indicators for cold chain integrity. Temperature sensitive logistics are treated as a critical component of resilient infrastructure, particularly for food and medical supply chains, demonstrating how smart sensing materials have the potential to reduce spoilage, waste, and risk in distributed supply networks.

Anwar Khitab and colleagues investigate, in **Reengineering Ancient Materials for Durable, Low-Carbon Structures**, how ancient materials and construction practices can be reengineered to produce durable, low carbon structural solutions, linking historical material knowledge with contemporary sustainability imperatives in the built environment, potentially reducing the carbon footprint of infrastructure.

Designing and Verifying Computational Models for Human-Agent Teamwork in Future Cities by Alexandros Konios and Leon Goncharov focuses on the design and verification of computational models that describe human-agent teamwork in the context of future cities. It frames urban infrastructure as a sociotechnical system in which humans and autonomous agents must coordinate reliably through modelling human-agent interaction with impact on the governance and operation of smart urban systems.

Multifunctional Hybrid Hierarchical Composites by Patrick Lee and colleagues examines multifunctional hybrid hierarchical composites designed to deliver enhanced mechanical and possibly additional functional properties within a single material system. It considers how advanced composites

can underpin lighter, stronger, and more resilient infrastructure components, improving the durability and efficiency of future infrastructure.

Elizabeth McCormick's **Building Health: Resilient Building Materials for Global Health and Sustainability** investigates building materials that support both resilient structures and global health outcomes, linking material choice to indoor environmental quality and sustainability, by treating buildings as health relevant infrastructure rather than neutral shells, examining the relationship between materials, health, and sustainability, innovation in material selection or design strategies, and potential building standards and policy.

In **AeroFeathers: Biomimetic Propellers with 3D-Printed Flexible Fibers for Quieter Drones**, Bisham Sharma and colleagues explore biomimetic propellers incorporating 3D printed flexible fibres to reduce drone noise. Innovation in biomimetic propeller design addresses acoustic pollution and performance in aerial systems that increasingly interact with urban and natural environments.

The **Artificial Intelligence and Augmented Intelligence** theme explores how artificial intelligence is reshaping governance, industry, public services and daily life, and how human capabilities can be extended rather than displaced by computational systems. It encompasses cognitive cities, digital citizenship, cybersecurity, machine learning, data science, AI-enabled personalisation, human-AI collaboration, and the ethical and governance frameworks required to guide responsible deployment. This theme draws on computer science, design, law, ethics, public administration, behavioural science and systems engineering, and considers how AI can improve resource use, strengthen decision-making, support healthcare and industry, and create new forms of civic participation, while also addressing risks and inequities.

Baseline Evaluation for Enhancing Human-Robot Collaboration (HRC) in Industry 5.0 Manufacturing from Erick Cedillo and colleagues establishes a multimodal psychophysiological baseline for human-robot collaboration during cobot-assisted assembly tasks. It shows how AI enabled sensing and modelling can support adaptive, human-centred Industry 5.0 systems, offering insight into operator stress and fatigue signatures, innovation in multimodal baseline design, and impact for developing responsive cobot strategies.

Wahbi K. El-Bouri and Rémi J. Hernandez develop, in **Digital Twins of the Retina: A Computational Framework for Personalised Microvascular Health Assessment**, image-based retinal digital twins that simulate individualised haemodynamics, validate flow metrics against literature, and model disease scenarios such as diabetic retinopathy. Their work shows how AI-supported computational modelling can personalise diagnostics and risk prediction in ophthalmology, highlighting innovation in digital twin construction and insights into microvascular biomarkers such as MTT and CTH.

In **The Internet of Beings: The Nightmares and Dreams of Digitalising Human Bodies**, Francesco Grillo outlines a conceptual framework for the “Internet of Beings,” examining how the integration of bodies, sensors, and AI could transform healthcare, pharmaceuticals, insurance, and geopolitics. It interrogates the sociotechnical, ethical, and economic implications of embedding AI within human

biological data systems, considering competing futures of digital embodiment and identifying policy and governance challenges.

Jeremy Howick proposes a cultural AI empathy assistant that augments clinicians' ability to recognise culturally specific expressions of distress, grounded in systematic reviews, harm databases, and ethical frameworks, in **Augmenting Human Empathy: AI-Assisted Solutions for Cross-Cultural Healthcare Communication**. This research positions AI as a mediator that enhances, rather than replaces, empathic human-patient communication in cross-cultural contexts.

Iasef Md Rian presents **An Integrated ARFEMAI System for Real-Time Structural Simulations and "XRay" Visualization of Heritage and Aging Buildings**, research which develops an integrated framework that generates digital twins, trains AI surrogate models on FEM outputs, and overlays real-time structural insights onto heritage buildings through augmented reality, demonstrating how AI can accelerate structural diagnostics and enable non-invasive, immersive conservation workflows for scalable heritage preservation.

AI-Driven XR Platform for Cognitive and Motor Empowerment in Young Students with Disabilities, by Mario Rodriguez presents an AI-adaptive XR platform that personalises cognitive and motor training for young adults with disabilities, validated through a pilot study showing improvements in memory, reaction time, and coordination. It shows how AI-driven personalisation enhances accessibility, inclusivity, and learning outcomes in immersive environments.

In **Revolutionizing Filmmaking: Artificial Intelligence Driven Motion Control with the Cinema Camera Robot**, Ishwar Singh and colleagues, in collaboration with AXIBO, introduce a low cost, modular, portable and intelligent solution to enable the democratisation of advanced filmmaking techniques across virtual production, VFX, and autonomous cinematography, with deployments at major studios and for creators at all scales.

The **Environmental Sustainability and Climate Action** theme addresses the urgent need to transform production, consumption and resource management, to mitigate climate change and protect ecological systems. It encompasses sustainable cities, renewable energy, green mobility, biodegradable materials, conservation, biodiversity, circular economy models, sustainable construction, pollution reduction and safer food systems. The theme draws on environmental science, engineering, materials research, design, agriculture, public health and policy, reflecting the interconnected nature of environmental challenges, and considers how industries can decarbonise, how waste can be reduced, how ecosystems can be restored and how communities can adapt to changing climatic conditions.

Faris Almalki presents **Integration of Deep Learning with CubeSat Technologies for Environmental Monitoring**, an intelligent CubeSat framework combining adaptive MIMO antennas, ANNs for link budget optimisation, YOLOv9 for object detection, and blockchain for secure data transmission across four environmental monitoring tasks (water detection, tree counting, vegetation assessment, oil spill detection), demonstrating how low cost, rapidly deployable space systems can strengthen climate action capabilities in regions with limited terrestrial monitoring infrastructure.

SEAWEED FOAM. A bio-foam material for home-compostable packaging products by Austėja Platukyte develops a fully organic, home compostable seaweed-based foam as an alternative to petrochemical and food-based packaging foams, validated through material testing, prototyping, and public exhibitions. It contributes to how marine biomass can support circular design, reduce packaging waste, and avoid competition with agricultural land.

Chinaedu Maduagwu's chapter, **Advancing Circular Economy through Ad-Tech for Optimizing Future Manufacturing**, proposes a digital platform that merges Ad-tech behavioural analytics, lifecycle assessment, and real-time inventory data to drive circular manufacturing, product returns, and resource recovery. It reframes consumer engagement as a critical lever for circularity, enabling manufacturers to close material loops through predictive nudging and personalised sustainability interventions.

Transesterification Optimization of Vhembe Macadamia Nuts Oil into Biodiesel Using Inorganic KOH Catalyst, by Mamookho Elizabeth Makhatha and colleagues optimises biodiesel production from macadamia nut oil using KOH catalysis and Box-Behnken statistical modelling, achieving a 91% yield and ASTM compliant fuel properties, which demonstrates a viable, non-food, regionally abundant feedstock for renewable fuel production in South Africa with potential impact through rural economic benefits and reduced reliance on fossil diesel.

Transforming Agricultural and Plant-based Byproducts into Compostable Hygiene Materials for a Circular Economy by Rashmi Prakash describes the extraction of cellulose fibres from agricultural residues to produce high performance fluff pulp and nonwovens, and demonstrates that prototype menstrual pads achieve 96.7% disintegration under ISO 16929 composting conditions. The research shows how agricultural waste streams can replace cotton, bamboo, wood pulp, and plastics in absorbent hygiene products, reducing landfill burden and providing a credible pathway to circular, low carbon hygiene products.

Shabib Al Rashdi and colleagues describe, in **AI-Optimised Green Hydrogen Production from Biomass and Wastewater with Integrated CO₂ Capture Pathways via Solar-Fenton and Natural Catalysts**, how wastewater valorisation and solar driven processes can reduce freshwater demand, emissions and energy costs in hydrogen production, particularly in arid regions, aligning with Oman Vision 2040 and scalable national hydrogen strategies.

Patrick Rice and Walter Schurtenburger describe the development of a pilot project for sustainable fuel production with zero carbon dioxide (CO₂) emissions in **Using Hydrokinetic Energy for Green Hydrogen and Green Oxygen Production**. A floating platform equipped with patented hydrokinetic turbines generates continuous power from the Gulf Stream to desalinate seawater and produce green hydrogen and oxygen offshore, demonstrating a zero carbon, cable-free marine energy system that supports both renewable fuel production and onshore aquaculture operations.

Dipa Roy and colleagues engineer hybrid composites from waste mixed plastics, waste glass fibres, and recycled carbon fibres, validating their structural performance in C-sections and high-velocity impact tests in their chapter, **Mixed Waste Plastics Derived Composites for Flood and Hurricane Protection**,

which demonstrates how low value waste streams can be transformed into disaster resilient infrastructure materials that outperform plywood, and meet hurricane resistance standards.

Leveraging AI-coupled Digital Twin Ecosystems for all Sustainable Development Goals in the Built Environment by Noha Saleeb presents the FRESH-BIM/FRESH-DT ecosystem integrating AI, digital twins, IoT telemetry, and VR/AR to optimise heritage restoration, building performance, and lifecycle sustainability across all 17 United Nations SDGs, demonstrating how intelligent, data driven systems can reduce waste, improve energy performance, enhance social equity, and support national scale heritage revitalisation.

Chosel Lawagon and colleagues present **Simultaneous Selective Recovery of Lithium and Cobalt from Spent Lithium-ion Batteries using Modified Bipolar Membrane Electrodialysis**, in which they describe a modified bipolar membrane electrodialysis process that simultaneously recovers high purity lithium hydroxide and cobalt hexacyanoferrate from spent lithium-ion battery leachates with >90% efficiency, reduced chemical inputs, and significantly lower energy demand, offering a scalable, low waste, low carbon recycling pathway.

The theme of **Socio-Economic Empowerment and Innovation** examines how societies can create fairer economic opportunities, strengthen governance and support innovation that benefits diverse communities. It encompasses the dynamics of contemporary labour markets, gender equality, diversity, micro-enterprise, technology for social good, policy design and the infrastructures that enable inclusive growth. The theme draws on economics, sociology, political science, design, technology and development studies, and considers how digital tools can expand access to services, how small-scale entrepreneurship can be supported, how governance structures can be improved and how innovation can be directed toward social rather than purely commercial outcomes.

John Gershenson and colleagues, in their chapter **Tools2Thrive: A Scalable Tool Rental Model for Smallholder Farmers in Kenya** report on a year-long, evidence-driven trial of a community based organisation-run tool rental model that expanded from 20 tools and 549 farmers to 300 tools and nearly 6,000 members, demonstrating that structured access to basic hand tools significantly increases farmer productivity, reduces labour time, and generates reinvestable revenue for community organisations. It shows how low cost, community embedded innovation can strengthen rural livelihoods, build organisational capacity, and create scalable socioeconomic infrastructure across the Global South.

Katherina Kuschel analysed 34 US-based podcast episodes to reveal that midlife entrepreneurship is driven less by technical training and more by narratives of identity reinvention, purpose, and navigating complex life transitions. **The second act of Life: Unveiling podcast narratives of purpose and reinvention among midlife entrepreneurs** positions midlife founders as a dynamic entrepreneurial demographic whose socioeconomic participation is shaped by wellbeing, relationships, and financial restructuring.

In **Eco-Efficient Valorisation of Spent Yeast: Protein and β -Glucan Fractions Recovery for Health-Promoting Applications**, Joelle Nader and colleagues present an integrated green processing strategy that converts spent yeast into high purity protein and β -glucan fractions, achieving 40-45% higher

extraction yields and improved thermal stability with significantly lower environmental footprint compared to traditional techniques. It demonstrates how circular bioeconomy approaches can generate impact through scalable, low waste valorisation pathways.

Willis Owino and colleagues present **Innovative Invasive Cactus Management: A Sustainable Solution for Kenya's Rangelands**, in which they document a novel intervention that converts invasive *Opuntia stricta* into nutrient dense livestock pellets, with trials showing goats gaining up to 9 kg in 91 days while simultaneously reducing rangeland degradation. Their research shows measurable impact on animal performance gains, innovation in transforming an ecological threat into a feed resource, and insight into scalable models that create green jobs for women and youth.

Alejandro Robledo and Domagoj Bui present **Next-Generation Community Hubs for Socio-Economic Empowerment: A Pilot Human-Centered Framework and Participatory Digital Twin Approach**. Their work introduces a human-centred, mixed methods, and Digital Twin-enabled framework for co-designing multifunctional community hubs that integrate mobility, essential services, and participatory planning, demonstrating how immersive simulations and structured stakeholder engagement can democratise infrastructure planning and address access inequities across rural, suburban, and urban contexts.

Weaving Economic Dignity: A Framework for Re-Engineering Value with Botswana's Heritage Basketry Artisans, by Keiphe Setlhatlhanyo and colleagues exposes systemic inequities in Botswana's basketry value chain-middleman exploitation, policy neglect, and erosion of intergenerational knowledge, based on fieldwork with rural women weavers. It proposes a four strand framework (codesigned innovation, fairtrade governance, youth digital empowerment, and policy integration) to reposition artisans as primary economic beneficiaries.

In **The Re-habitualisation of Boycotts: From Disruption to Everyday Life**, Wang-Shu Liu theorises "rehabilitation" as the long-term process through which boycott-driven consumption disruptions evolve into new everyday routines, drawing on practice theory and the Fair Trade movement as an illustrative case. It reframes political consumerism as a socioeconomic practice that embeds political meaning into ordinary life.

The **Open** theme provides space for research that does not sit neatly within a single category or that spans multiple domains. It encompasses cross-disciplinary innovation, novel approaches to longstanding problems, experimental methods, early-stage prototypes and disruptive technologies whose implications are not yet fully understood. The theme values intellectual curiosity, methodological diversity and conceptual risk-taking, acknowledging that progress often begins with exploratory work that challenges established assumptions. As a body of work, it underscores the importance of openness in academic inquiry and the generative potential of research that resists categorisation.

Jésus Carbajo and colleagues present the development and testing of PET-based acoustic panels made from recycled plastic bottles in **Eco-friendly and biocompatible materials for noise reduction in healthcare environments**, demonstrating high acoustic absorption, low toxicity, and strong biocompatibility for healthcare settings, showing how sustainable materials can simultaneously

improve patient wellbeing, reduce environmental impact, and meet stringent clinical safety requirements, while also driving innovation through circular economy material engineering.

In **Beyond the Object: Product and Furniture Design as Critical and Social Practice**, Jason Cleverly and Adrienne Bennie examine how interdisciplinary, socially engaged design pedagogies reposition designers as facilitators who use ethnographic and participatory methods to interrogate everyday practices and co-create contextually responsive artefacts. They demonstrate how design education can cultivate practitioners capable of addressing complex socioecological challenges by reframing design as social practice, and through student led interventions embedded in real communities.

Prototype of the Sustainable Tourism Promotion Model based on Technology 4.0 in post-conflict regions. Case study: La Palma and Yacopí (Colombia), by Melva Inés Gómez-Caicedo and colleagues, presents a Technology 4.0 enabled sustainable tourism promotion model co-created with communities in two post conflict Colombian municipalities, integrating AR/VR tools, territorial characterisation, and participatory governance. It shows how digital innovation can support territorial recognition, economic revitalisation, and community centred development in regions recovering from violence.

Gauri Karanjkar and Reena Pandey analyse the role of handknitting in Uttarakhand as a vehicle for intergenerational bonding, cultural transmission, and community cohesion, while documenting the decline of youth participation due to economic and social pressures, in **Study of Intergenerational Craft and Revival in Himalayan Communities**. They highlight the fragility of intangible heritage systems and the need for revival strategies that integrate livelihoods, identity, and contemporary relevance, and articulation of pathways for sustaining Himalayan craft traditions.

Dario Krpan describes, in **Agentic AI for Sustainable Behaviour: A Coaching Framework and Workflow**, a multiagent AI coaching system that uses behavioural science, personalised diagnostics, and adaptive interventions to help individuals adopt and maintain low-carbon lifestyles across multiple domains, offering a scalable, evidence-based digital infrastructure for transformative behavioural change aligned with sustainability goals.

In **Design for Change: Transformational cross-cultural and transdisciplinary learning experiences to solve global healthcare sustainability challenges**, Lisa Scharoun and colleagues describe a cross-cultural, transdisciplinary design sprint model that brings together students to co-create sustainable healthcare solutions through experiential and problem-based learning. Their research investigates how global collaboration and design thinking can generate context-sensitive responses to healthcare waste, emissions, and inequities.

The **Speculative** theme invites research that looks beyond current constraints to imagine alternative futures, emerging paradigms, and untested possibilities. It encompasses speculative design, early-stage insights, exploratory methods, reimagined systems and interdisciplinary ventures into new technological or conceptual frontiers, encouraging work that probes the limits of what is known, asks what might be possible, and considers how future societies could be organised, governed, or experienced. It recognises that speculation is a tool for exploring uncertainty and shaping long-term trajectories.

Livia Alexander argues in **GameShift Futures: Reimagining the University Through Speculative Play** that gaming and immersive media, framed as expanded media, offer speculative, systems-based methodologies for rethinking higher education pedagogy and institutional practice, demonstrated through the prototype GameShift platform. This research positions universities as iterative, participatory futures laboratories.

Prototypes of Personalisation and Customisation for Next-generation Medicines, by Subhan Banerjee surveys pharmaceutical additive manufacturing (3D/4D printing) as a platform for producing personalised, patient-specific drug delivery systems, supported by experimental outputs from the author's Lab of Additive Manufacturing in Pharmaceuticals (LAMP) laboratory. Emerging fabrication technologies can transform therapeutic precision, dosage control, and patient-centred pharmaceutical design.

In **The Role of Design in Challenging Exclusionary Urban Spaces**, Adrienne Bennie examines hostile architecture in London and uses 3D printed replicas of exclusionary design elements as pedagogical and public engagement tools to expose spatial injustice. The paper shows how design can materialise and critique the politics of public space, enabling new forms of social awareness and discourse, demonstrating insight into affordances and exclusion, and transferable tools for community, professional, and policy engagement.

Yoram Chisik explores the intersection of food and play, analysing the physical affordances of food and the challenges of integrating gustatory, olfactory, and embodied eating experiences into interactive systems, in the chapter **Gastroludology: Gastronomy Meets Ludology**. The research reframes food as a medium for human-technology interaction, sensory communication, and playful experimentation, proposing new mechanics for food-based play.

From Walls to Worlds: Co-creating Heritage Narratives with AR Murals by Agnes Michalczyk investigates how augmented reality murals can support equitable heritage management by enabling participatory storytelling, digital restoration, and community-centred cultural representation, drawing on case studies from Cairo and international contexts. It considers how immersive technologies can democratise heritage narratives and reconnect marginalised communities with their tangible and intangible cultural assets.

Owain Pedgley and Bahar Şener's chapter, **Design for Emergency and Disaster Scenarios: Concepts that Serve Humanity**, presents 47 student-generated industrial design concepts for emergency and disaster scenarios, analysed across the disaster readiness and response framework to reveal gaps, opportunities, and high-potential innovations. Design education can generate speculative yet actionable solutions for emergency response, while highlighting the need for cross-sector collaboration to realise them.

Back to the Future: Exploring the Untapped Potential of Freehand Weaving by Tania Ursomarzo repositions indigenous freehand weaving, specifically khoos, as an architectural material technology through collaborative experimentation with Egyptian artisans and hybrid analogue-digital prototyping. It examines how ancestral craft knowledge can inform sustainable, culturally grounded, and materially

intelligent design futures, proposing new artisan-designer collaborations for contemporary architecture.

The almost 60 chapters presented across the seven themes reveal a set of cross-cutting insights that illuminate the developing character of contemporary research and its capacity to address complex global challenges. Across the programme there is a clear movement towards integrated approaches that treat technological, environmental, social, and economic systems as interdependent. This shift is not rhetorical but methodological, shaping the questions posed, the evidence gathered, and the forms of analysis deployed. The work demonstrates that the most pressing issues of the present moment often benefit from cross-domain expertise, and that effective solutions increasingly emerge from collaborations that combine scientific, engineering, design-led, and socially grounded perspectives. This interdisciplinarity underpins the intellectual coherence of the themes as a whole.

Several patterns recur across the papers, including the prominence of circularity, expressed through the recovery of critical materials, the revitalisation of traditional crafts, the redesign of food systems, and the reconfiguration of urban and infrastructural assets. Circularity appears as a practical organising principle that links environmental sustainability with economic resilience and technological innovation. A second pattern is the emphasis on concerns about access to healthcare, the distribution of environmental burdens, the governance of digital systems, and the empowerment of communities. A third pattern is methodological hybridity: many of the projects presented in these chapters combine laboratory experimentation, digital modelling, prototyping, ethnography, participatory design, and speculative inquiry. This hybridity reflects a recognition that complex challenges require forms of knowledge that are empirical yet situated, technical yet socially attuned, and capable of supporting both immediate application and long-term progress.

The seven themes reveal convergences that might not be immediately apparent. Work on artificial intelligence shares concerns with heritage preservation about authorship, agency, and the risks of technological dependency. Research on wellbeing aligns with environmental sustainability through its attention to material exposures, urban form, and the design of supportive environments. Studies of socio-economic empowerment intersect with infrastructure and mobility research through their focus on access, safety, and the conditions for participation in economic and civic life. These convergences indicate that global priorities are not neatly divisible into sectors but instead form a network of overlapping challenges that require coordinated responses. They also suggest that the boundaries between technological, social, and environmental research are becoming increasingly porous, creating opportunities for new forms of collaboration.

A number of shared concerns run through the papers. These include the ethical deployment of emerging technologies, the reduction of waste and harm, the design of systems that are resilient in the face of uncertainty, and the need to ensure that innovation benefits the widest range of communities. The work highlights the importance of responsible governance, whether in the management of data, the stewardship of natural resources or the design of public services. It also underscores the need for infrastructures that can adapt to changing climatic, demographic, and technological conditions. These

concerns reflect a broader shift toward anticipatory thinking, in which research is expected not only to respond to present challenges but also to prepare for future ones.

Many projects propose modular, decentralised, or low-waste approaches that can be scaled or adapted to different contexts. Others emphasise the value of local knowledge, whether in the form of artisanal craft traditions, community-based heritage practices, or users navigating complex systems. These approaches suggest that innovation is perhaps most effective when it is accountable to the contexts in which it operates, and when it recognises that technological solutions must be embedded within social and environmental realities.

The themes also point toward emerging global priorities. These include resilience, sustainability, ethical governance, resource stewardship, and the design of systems that can support well-being across the course of life. There is a growing recognition that technological progress must be aligned with environmental limits, social expectations, and long-term public value. This alignment is evident in work on renewable energy, sustainable materials, digital healthcare, circular manufacturing, mobility futures, and the governance of artificial intelligence. It is also visible in the attention given to vulnerable populations, whether through improved access to healthcare, safer infrastructures, or more inclusive economic opportunities.

Taken together, the chapters demonstrate that the whole is more than the sum of its parts. When viewed collectively, they reveal a research landscape that is converging on shared principles even as it spans diverse domains. The themes offer a coherent intellectual backbone for future collaboration between academia, industry, policymakers, and civil society. They show that meaningful progress depends to a significant extent on the ability to connect insights across fields, and that the most promising innovations are those that combine technical excellence with social purpose and environmental responsibility. The work presented in these chapters suggests that the future of research lies not in isolated breakthroughs but in integrated systems of knowledge capable of shaping futures that are both ambitious and achievable.

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Part I
Wellbeing and Health Futures

Chapter 1

Plasma Polymerized Nanoparticles: From Cell Imaging to Cancer Therapy

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Abstract

Cancer remains a leading cause of mortality worldwide, lacking effective targeted therapies. In Australia alone, more than 50,000 people die from cancer each year. Polymeric nanoparticles (NPs) are promising platforms for cancer nanomedicine due to their tuneable physicochemical properties, biocompatibility, and capacity for functionalisation. However, conventional wet-chemical synthesis often relies on toxic solvents, complex purification, and limited scalability, restricting clinical translation. Plasma polymerisation offers a dry, solvent-free, and sustainable alternative for generating polymeric nanoparticles (PPNs) with unique surface chemistries and embedded long-lived radicals that enable direct covalent attachment of biomolecules without chemical linkers. Here, we demonstrate the versatility of PPNs by separately conjugating two fluorescent dyes (Nile Blue A and Rhodamine-1) for imaging, and two cytotoxic agents (Doxorubicin and Curcumin) for therapy. Fluorophore-conjugated PPNs facilitated visualisation of cellular uptake in A549 lung and MDA-MB-231 breast cancer cells, confirming their potential for diagnostic imaging. Therapeutic PPN formulations (PPN-DOX and PPN-Cur) localised around the nucleus and membrane of MDA-MB-231 cells and significantly reduced cell viability, with cytotoxicity corroborated by LDH leakage assays. These findings demonstrate the multifunctionality of PPNs as efficient nanocarriers for combined imaging and therapeutic applications. This streamlined, chemical-free approach overcomes key limitations of polymeric nanomedicine, including the reliance on hazardous solvents, multistep conjugation, and scalability issues. The PPNs prototype represents a paradigm shift in cancer nanomedicine: a universal, sustainable, and adaptable drug delivery platform, transforming precision therapies with global relevance and tangible impact for humanity.

Keywords: *Plasma polymerization, Nanoparticles, Cancer Therapy, Imaging, Drug Delivery*

Introduction

Cancer remains one of the highest causes of mortalities worldwide, ranking second behind ischemic heart disease, with about 8.97 million deaths in 2019¹. The high mortality is partly driven by the intrinsic heterogeneity of cancer subtypes, which hinders the development of universal treatments. Despite advances in chemotherapy, pharmacotherapy, and radiotherapy, clinical outcomes are often limited by suboptimal efficacy, systemic toxicity, and non-specific biodistribution, leading to damage of healthy tissues². Furthermore, multidrug resistance significantly reduces the effectiveness of these interventions³.

Free drugs, administered without a drug delivery system, face pharmacokinetic limitations such as rapid clearance, poor stability, and low tumour accumulation⁴. Nanoparticle (NP)-based drug delivery systems address these issues by encapsulating or conjugating drugs within nanoscale carriers⁵, improving solubility, prolonging circulation, and enhancing tumour accumulation via the enhanced permeability and retention effect⁶. Among these, NP-based carriers, polymeric NPs, are especially attractive due to their tuneable structure, biocompatibility, and ability to navigate complex biological environments⁷. Their amphiphilic matrices enable colloidal stability, functional surfaces allow ligand conjugation, and stimuli-responsive features permit triggered drug release. However, wet chemical synthesis is often hampered by toxic solvents, multiple purification steps, and poor scalability, limiting clinical translation^{8,9}.

¹Camilla Mattiuzzi and Giuseppe Lippi, "Current Cancer Epidemiology," *Journal of Epidemiology and Global Health* 9 (2019): 217–22, <https://doi.org/10.2991/jegh.k.191008.001>

²Zihan Wang et al., "Poly Ethylene Glycol (PEG)-Based Hydrogels for Drug Delivery in Cancer Therapy: A Comprehensive Review," *Advanced Healthcare Materials* 12, no. 18 (April 13, 2023): e2300105, <https://doi.org/10.1002/adhm.202300105>

³Hira Choudhury et al., "Rising Horizon in Circumventing Multidrug Resistance in Chemotherapy With Nanotechnology," *Materials Science and Engineering C* 101 (2019): 596–613, <https://doi.org/10.1016/j.msec.2019.04.005>

⁴Boyu Su et al., "Therapeutic Regulation of Epigenetics in Cancer Treatment Through Drug Delivery Systems," *Nano Today* 56 (2024): 102251, <https://doi.org/10.1016/j.nantod.2024.102251>

⁵Bijaideep Dutta, K.C. Barick, and P.A. Hassan, "Recent Advances in Active Targeting of Nanomaterials for Anticancer Drug Delivery," *Advances in Colloid and Interface Science* 296 (August 18, 2021): 102509, <https://doi.org/10.1016/j.cis.2021.102509>

⁶Michael J. Mitchell et al., "Engineering Precision Nanoparticles for Drug Delivery," *Nature Reviews Drug Discovery* 20 (2021): 101–24, <https://doi.org/10.1038/s41573-020-0090-8>

⁷Karine Cappuccio De Castro, Josiel Martins Costa, and Maria Gabriela Nogueira Campos, "Drug-loaded Polymeric Nanoparticles: A Review," *International Journal of Polymeric Materials* 71, no. 1 (August 7, 2020): 1–13, <https://doi.org/10.1080/00914037.2020.1798436>

⁸Elmer S. Austria and Behnam Akhavan, "Polymeric Nanoparticle Synthesis for Biomedical Applications: Advancing from Wet Chemistry Methods to Dry Plasma Technologies," *Nanoscale* 17, no. 21 (2025): 13020–56, <https://doi.org/10.1039/d5nr00436e>

⁹Elmer Austria et al., "Breaking Biological Barriers: Engineering Polymeric Nanoparticles for Cancer Therapy," *Nano Today* 60 (2025): 102552, <https://doi.org/10.1016/j.nantod.2024.102552>

Plasma polymerisation provides a solvent-free and sustainable method for synthesising polymeric NPs¹⁰. It proceeds through a fragmentation-recombination pathway, where cold temperature plasma discharges of precursor organic gases or vapours break monomers into reactive species, including electrons, ions, radicals, and molecular fragments. Such highly reactive species undergo recombination and crosslinking, forming highly branched and crosslinked polymeric nano-thin films or NPs¹¹. The resulting NPs contain long-lived radicals that act as anchorage sites for covalent biomolecule attachment¹², eliminating the need for chemical linkers or toxic solvents.

Here, we demonstrate the versatility of plasma-polymerized nanoparticles (PPNs) by conjugating two fluorescent dyes (Nile Blue A, Rhodamine-1) and two therapeutic agents (Doxorubicin, Curcumin) for cancer therapy. Fluorophore-conjugated PPNs enabled real-time tracking of cellular uptake, while drug-conjugated PPNs suppressed cancer cell proliferation, highlighting their dual role in imaging and therapy. This streamlined, chemical-free approach addresses key challenges in polymeric nanomedicine, including scalability and environmental sustainability. This technology offers a transformative platform for advancing multifunctional NPs in cancer diagnosis and treatment.

Materials and Methods

PPNs were generated in a stainless-steel vacuum chamber (Figure 1a) using acetylene, nitrogen, and argon as precursor gases at flow rates of 6, 10, and 3 sccm, respectively. The chamber was maintained at a base pressure of 5×10^{-5} Torr. Plasma discharge was initiated by applying 150 W of radiofrequency (13.56 MHz) power to the top electrode for 390 s, as previously described in our earlier works¹³⁻¹⁵. The resulting PPNs were subsequently collected in a commercial 24-well cell culture plate.

Covalent surface functionalisation of PPNs with Nile Blue A (NB), Rhodamine-1 (Rho1), Doxorubicin (DOX), or Curcumin (Cur) was achieved through a single-step incubation. Each biomolecule was added to PPN suspensions in Milli-Q water at a ratio of 200 pg per 100,000 particles and agitated for 1 h at room temperature. The resulting conjugates were purified by centrifugation (8000 rcf), followed by

¹⁰Miguel Santos et al., "Plasma Synthesis of Carbon-Based Nanocarriers for Linker-Free Immobilization of Bioactive Cargo," *ACS Applied Nano Materials* 1, no. 2 (January 5, 2018): 580–94, <https://doi.org/10.1021/acsanm.7b00086>

¹¹Masoud Zhianmanesh et al., "Plasma Surface Functionalization: A Comprehensive Review of Advances in the Quest for Bioinstructive Materials and Interfaces," *Applied Physics Reviews* 10, no. 2 (2023): 021301, <https://doi.org/10.1063/5.0130829>

¹²Laura Libnan Haidar et al., "Direct Covalent Attachment of Fluorescent Molecules on Plasma Polymerized Nanoparticles: A Simplified Approach for Biomedical Applications," *Journal of Materials Chemistry B* 13, no. 5 (2025): 1666–80, <https://doi.org/10.1039/d4tb01515k>

¹³Behnam Akhavan et al., "Radical-functionalized Plasma Polymers: Stable Biomimetic Interfaces for Bone Implant Applications," *Applied Materials Today* 16 (2019): 456–73, <https://doi.org/10.1016/j.apmt.2019.07.002>

¹⁴Laura L. Haidar et al., "Surface-Active Plasma-Polymerized Nanoparticles for Multifunctional Diagnostic, Targeting, and Therapeutic Probes," *ACS Applied Nano Materials* 5, no. 12 (August 30, 2022): 17576–91, <https://doi.org/10.1021/acsanm.2c03213>

¹⁵Miguel Santos et al., "Substrate Geometry Modulates Self-assembly and Collection of Plasma Polymerized Nanoparticles," *Communications Physics* 2, no. 52 (May 20, 2019): 1–11, <https://doi.org/10.1038/s42005-019-0153-5>

resuspension in Milli-Q water. This washing cycle was repeated three times before resuspending the final product in 5 mL of PBS for material characterisation and in-vitro experiments.

Surface chemistry and elemental composition were analysed by X-ray photoelectron spectroscopy (XPS, Thermo Fisher K-Alpha+). Morphological features were examined by scanning electron microscopy (SEM, JEOL JSM 7800F), while hydrodynamic diameters were determined via dynamic light scattering (DLS, Malvern Zetasizer Nano ZS). Functional groups were identified by Fourier-transform infrared spectroscopy (FTIR, Bruker ALPHA with ATR diamond module). Radical content was assessed using electron paramagnetic resonance (EPR, SpinScanX, Adani). Fluorescence spectra of PPN-NB, PPN-Rho1, PPN-DOX, and PPN-Cur were recorded using a ClarioStar Plus plate reader (BMG Labtech) at excitation/emission maxima of 624/680, 560/584, 470/596, and 425/544 nm, respectively.

A549 (lung) and MDA-MB-231 (breast) cancer cells were seeded at 30,000 cells/dish and cultured overnight at 37 °C in a 5% CO₂ incubator. Cells were then incubated with either PPN-NB or PPN-Rho1 (50 µg/mL in Adv-DMEM) for 1 h. After treatment, cells were washed three times with PBS and resuspended in FluoroBrite™ DMEM. Confocal imaging was performed using an Olympus FluoView FV3000 microscope (excitation: 640 nm; emission: 655-735 nm). Image analysis was conducted with Fiji software.

The therapeutic potential of PPN-DOX and PPN-Cur was evaluated in MDA-MB-231 cells using Alamar Blue assay. Cells were seeded at 5000 cells/well in 96-well plates and allowed to adhere for 24 h. Samples containing varying concentrations of PPN-DOX or PPN-Cur were added and incubated for 48 h. Following treatment, 10 µL of resazurin reagent was introduced into each well and incubated for 4 h. Fluorescence was recorded at 570 nm using a ClarioStar plate reader. Cell viability was expressed relative to PBS-treated controls, with 5% SDS serving as a positive control. Data were processed in OriginPro 2022 (OriginLab, USA).

Results and Discussion

Plasma Polymerisation of NPs

PPNs are synthesised using a dry, linker-free and environmentally sustainable technology that harnesses plasma, the fourth state of matter, to initiate polymerisation. The process is conducted in a custom-built stainless-steel reactor operating under low pressure ($\sim 10^{-5}$ Torr), powered by a radiofrequency (RF) generator connected to the top electrode to generate a stable plasma discharge (Figure 1a). Within this plasma environment, the gaseous precursor mixture undergoes fragmentation into reactive species, which subsequently nucleate and aggregate into protoparticles, ultimately forming PPNs (Figure 1b).

PPNs benefit from favourable physicochemical properties which is crucial in its role as a nanoplatform for delivering biomolecular payload in the body. The PPNs created from a precursor gas mixture of argon, nitrogen, and acetylene are composed of carbon (64.1 atm%), nitrogen (28.3 atm%), and oxygen (7.6 atm%), as informed by the X-ray photoelectron spectroscopy (XPS) survey spectrum presented in Figure 2a. Scanning electron microscopy (SEM) imaging reveals that the PPNs have spherical morphology, with dry particle size ranging from 70 to 120 nm (Figure 2b and Figure 2c). The low

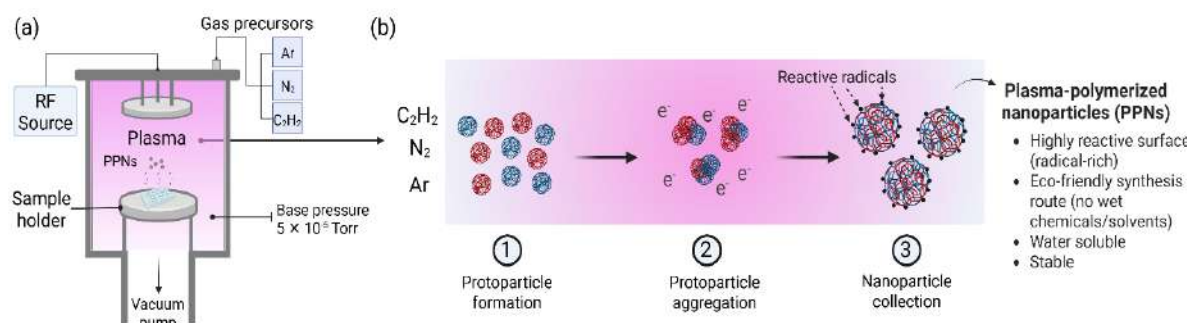


Figure 1: Schematic representation of the production of the PPN prototype. (a) Custom-built cylindrical vacuum chamber used for plasma polymerisation of NPs. (b) Synthesis pathway illustrating the plasma-induced fragmentation of precursor gases (C₂H₂, N₂, and Ar), leading to the nucleation and accretion of protoparticles. Once a critical mass is reached, the PPNs settle into a 24-well collection plate under gravitational force.

polydispersity index (PDI) value (<0.1) in water suggests monodispersity in aqueous solutions (Figure 2d), along with relatively small hydrodynamic size ($D_H = 190$ nm) as measured using dynamic light scattering (DLS), which are both important in overcoming biological barriers of delivery. PPNs contain surface functional groups such as hydroxyl, amine, nitrile, and carboxylic acid moieties as seen in the attenuated total reflectance - Fourier transform infrared (ATR-FTIR) spectra (Figure 2e). The relative abundance and composition of these moieties can be tuned by altering precursor gas composition, enabling tailored surface chemistries for specific applications such as covalent drug conjugation, targeted ligand attachment, or modulation of cellular interactions. The defining feature of PPNs is the presence of unpaired electrons or radicals in its nanostructure, detected through electron paramagnetic resonance (EPR) spectroscopy (Figure 2f), which gradually diffuse towards the material's surface. These radicals enable robust and chemical-free covalent attachment of virtually any biomolecule onto the PPN surface.

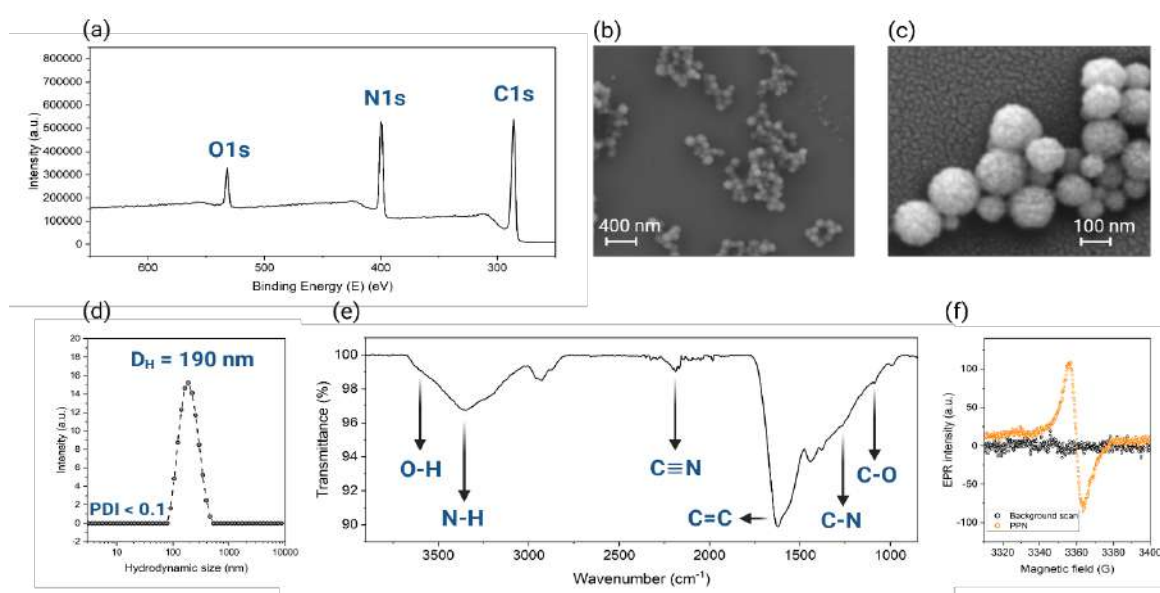


Figure 2: Physicochemical properties of PPNs enable it to become ideal nanoplateforms of transporting biomolecules. (a) X-ray photoelectron spectroscopy survey spectra of PPNs, (b-c) SEM micrographs, (d) dynamic light scattering spectra, (e) Fourier transform infrared spectra, and (f) electron paramagnetic resonance spectra of PPNs.

Covalent Attachment of Biomolecular Payload onto PPN Surfaces

To demonstrate the robustness and versatility of the PPN platform, four representative molecules (NB, Rho1, DOX, and Cur) were covalently conjugated in a single-step process under mild conditions without chemical linkers and toxic solvent. NB and Rho1 are fluorescent dyes commonly used in cellular imaging^{16,17}, while DOX and Cur are cytotoxic agents previously explored in cancer therapy¹⁸⁻¹⁹. Both PPNs and each respective payloads were dispersed in water (or ethanol for Cur) and were incubated for 1 h at room temperature (Figure 3a).

Following SDS washing, all four PPN formulations (PPN-NB, PPN-Rho1, PPN-DOX, and PPN-Cur) exhibited statistically significant increases in fluorescence intensity ($P < 0.0001$) compared to their unconjugated counterparts (Figure 4a). The retention of strong fluorescence after stringent washing confirms stable covalent bonding between the payloads and the PPN surfaces.

Beyond the observed fluorescence signals, further evidence of successful conjugation was obtained from the high-resolution XPS C1s spectra. Each molecule exhibited distinct surface functional groups, and these variations were consistently reflected in their corresponding C1s spectral peaks. The C1s spectrum of unconjugated PPN shows three characteristic components at binding energies (BE) of 284.9 eV (C–C/C–H), 286.4 eV (C–N/C–O), and 288.1 eV (C=O). Upon conjugation with NB, appeared at ~283.3 eV, corresponding to sp^2 -hybridised C=C from the phenoxazine moiety in Nile Blue A. In the case of Rho1, the relative abundance of the C–N species increased from 19.1% for the unconjugated PPN to 42.4% for the PPN-Rho1 due to the presence of amino groups on the central xanthene ring in Rho1. The shape of the high-resolution C1s peaks of PPN-DOX and PPN-Cur both display a defined shoulder peak at 286.4 eV which corresponds to an increase in C–N/C–O species. For DOX, this increase from 19.1% pre-conjugation to 30.9% after attachment came from the daunosamine sugar moiety. The ketone group in DOX also resulted to a 2.4% increase in C=O species. In contrast, the prominent shoulder peak in PPN-Cur is caused by increase in C–O species coming from the *o*-methoxy and phenolic groups in Cur. These two functional groups almost doubled the relative abundance of C–N/C–O species from 19.1% to 38.0% in PPN-Cur. Taken together, these data provide compelling evidence for the successful covalent attachment of all four biomolecules (NB, Rho1, DOX, and Cur) onto the nanoparticle surface, firmly validating the robustness and versatility of the PPN prototype.

¹⁶Haidar et al., “Direct Covalent Attachment of Fluorescent Molecules on Plasma Polymerized Nanoparticles: A Simplified Approach for Biomedical Applications.”

¹⁷Nian Kee Tan et al., “Ultrasensitive Dual Fluorophore-Conjugated Carbon Dots for Intracellular pH Sensing in 3D Tumor Models,” *ACS Applied Materials & Interfaces* 16, no. 36 (August 31, 2024): 47303–13, <https://doi.org/10.1021/acsami.4c10836>

¹⁸Oktay Tacar, Pornsak Sriamornsak, and Crispin R Dass, “Doxorubicin: An Update on Anticancer Molecular Action, Toxicity and Novel Drug Delivery Systems,” *Journal of Pharmacy and Pharmacology* 65, no. 2 (2013): 157–70, <https://doi.org/10.1111/j.2042-7158.2012.01567.x>

¹⁹Shiva Shakori Poshteh, Shohreh Alipour, and Pegah Varamini, “Harnessing Curcumin and Nanotechnology for Enhanced Treatment of Breast Cancer Bone Metastasis,” *Discover Nano* 19, no. 177 (November 11, 2024), <https://doi.org/10.1186/s11671-024-04126-1>

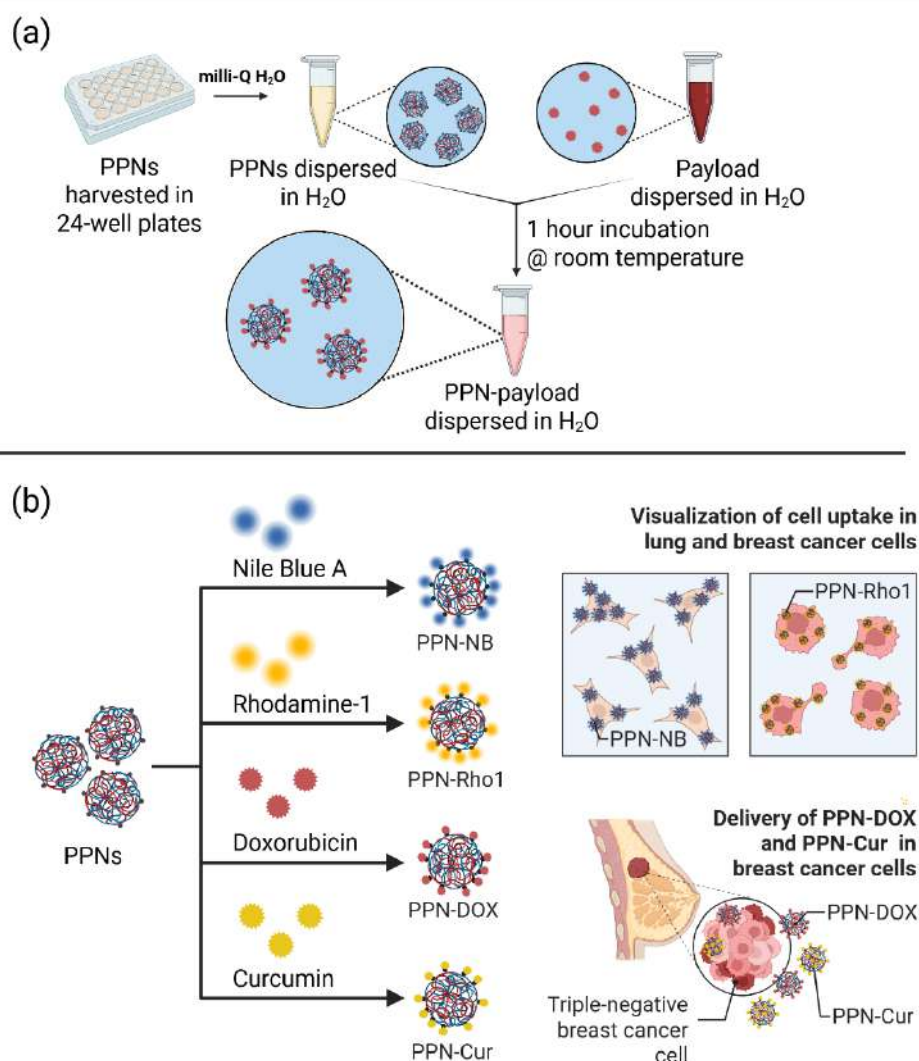


Figure 3: (a) Single-step, covalent conjugation of PPNs with payload. (b) PPNs were conjugated with fluorophore dyes (NB, Rho1) and cytotoxic agents (DOX, Cur) and were used for cell imaging and cancer therapy.

Cellular Uptake and Cytotoxicity Studies on PPNs

Nanoplatfoms such as PPNs can serve as carriers for delivering imaging agents to cells and tissues, with excellent potential in diagnostic imaging applications. The performance of fluorophore-labelled PPNs was evaluated by examining their cellular uptake across different cancer cell lines. The fluorescently tagged nanocarriers enabled direct visualisation of nanoparticle internalisation. Specifically, PPN-NB was incubated with A549 lung carcinoma cells, while PPN-Rho1 was introduced to MDA-MB-231 triple-negative breast cancer cells (Figure 3b).

As shown in the confocal laser scanning microscopy images presented in Figure 5a, A549 cells effectively internalized the PPN-NB formulation. After a 1-hour incubation, intracellular localisation was verified through the detection of blue fluorescence corresponding to the NB dye. In contrast, no fluorescence was observed in cells exposed solely to unconjugated PPN cores, validating that the detected emission originated exclusively from the conjugated NB fluorophore.

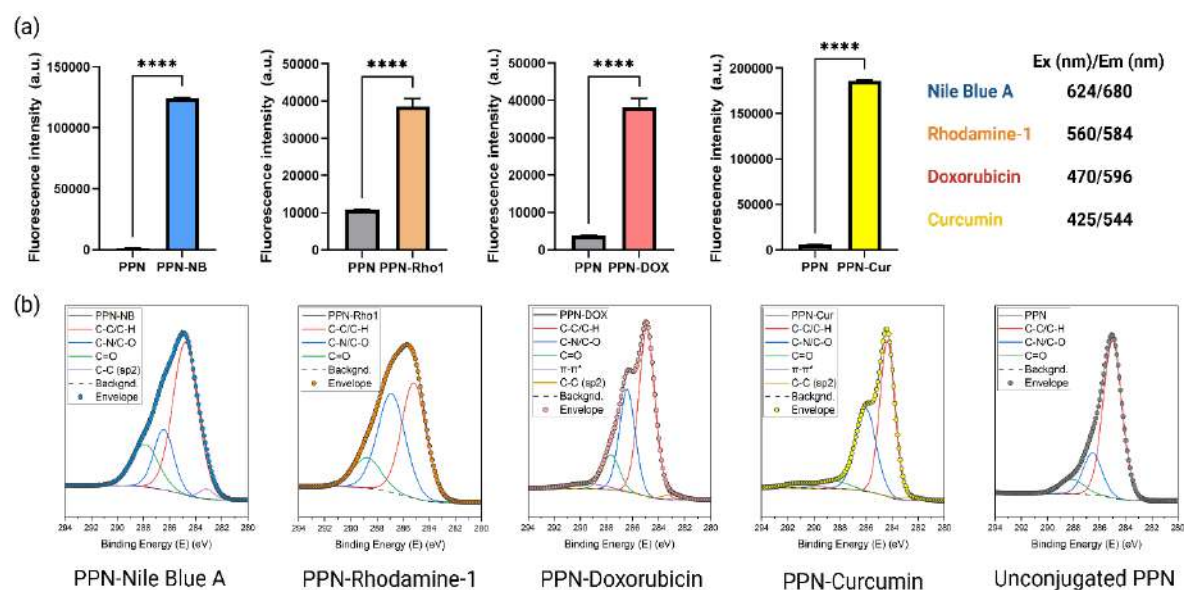


Figure 4: Covalent conjugation of biomolecules onto PPNs. (a) fluorescence intensities of PPN-NB, PPN-Rho1, PPN-DOX, and PPN-Cur. (b) High-resolution C1s XPS spectra of all samples, including the un conjugated PPN. All data are presented as mean $\pm$ SD ($n = 3$). Statistical significance is denoted as follows: (****) $P < 0.0001$.

Comparable results were obtained with PPN-Rho1, where uptake by MDA-MB-231 cells was confirmed through the detection of fluorescence signals in the red channel (Figure 5b). The cellular uptake studies demonstrate the adaptability of the PPN platform, allowing for the covalent conjugation of diverse fluorophores with distinct optical characteristics, a feature highly valuable for biomedical imaging applications. These results demonstrate that the PPN platform enables stable, linker-free conjugation of diverse fluorophores with distinct optical properties, supporting its adaptability for multimodal imaging in cancer diagnostics.

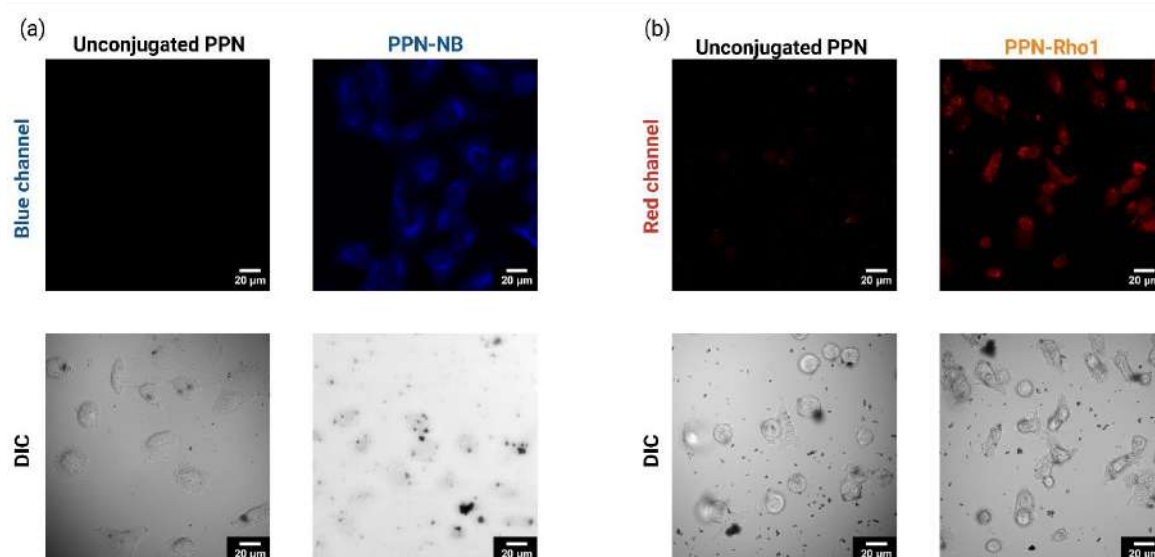


Figure 5: Successful cellular uptake is visualised using (a) PPN-NB in A549 lung cancer cells and (b) PPN-Rho1 in MDA-MB-231 breast cancer cells. In contrast, no fluorescence signals are observed in un conjugated PPNs which do not contain any fluorophores.

In addition to enabling diagnostic imaging, the PPN platform holds significant promise for targeted cancer therapy by facilitating site-specific delivery of therapeutic agents. Its stable, radical-rich surface

allows covalent conjugation of diverse drugs without the need for chemical linkers, offering a streamlined route to multifunctional nanocarriers.

To demonstrate this therapeutic potential, we conjugated two representative anticancer agents (DOX and Cur) onto PPNs, forming PPN-DOX and PPN-Cur, respectively (Figure 3b). The nanocarriers were incubated with MDA-MB-231 triple-negative breast cancer cells over 72 hours. After the first 24 h, confocal microscopy imaging of PPN-Cur (Figure 6a) and PPN-DOX (Figure 6b) display successful localisation and internalisation of the conjugated PPNs onto the MDA-MB-231 cancer cells. Furthermore, both PPN-Cur and PPN-DOX were found to localise predominantly around the nucleus and along the cell membrane of cancer cells, a distribution pattern considered advantageous for drug delivery applications. In contrast, the unconjugated PPNs do not show any fluorescence signals (Figure 6c), clearly indicating the need to tag with fluorescent molecules like Cur and DOX to track cellular uptake.

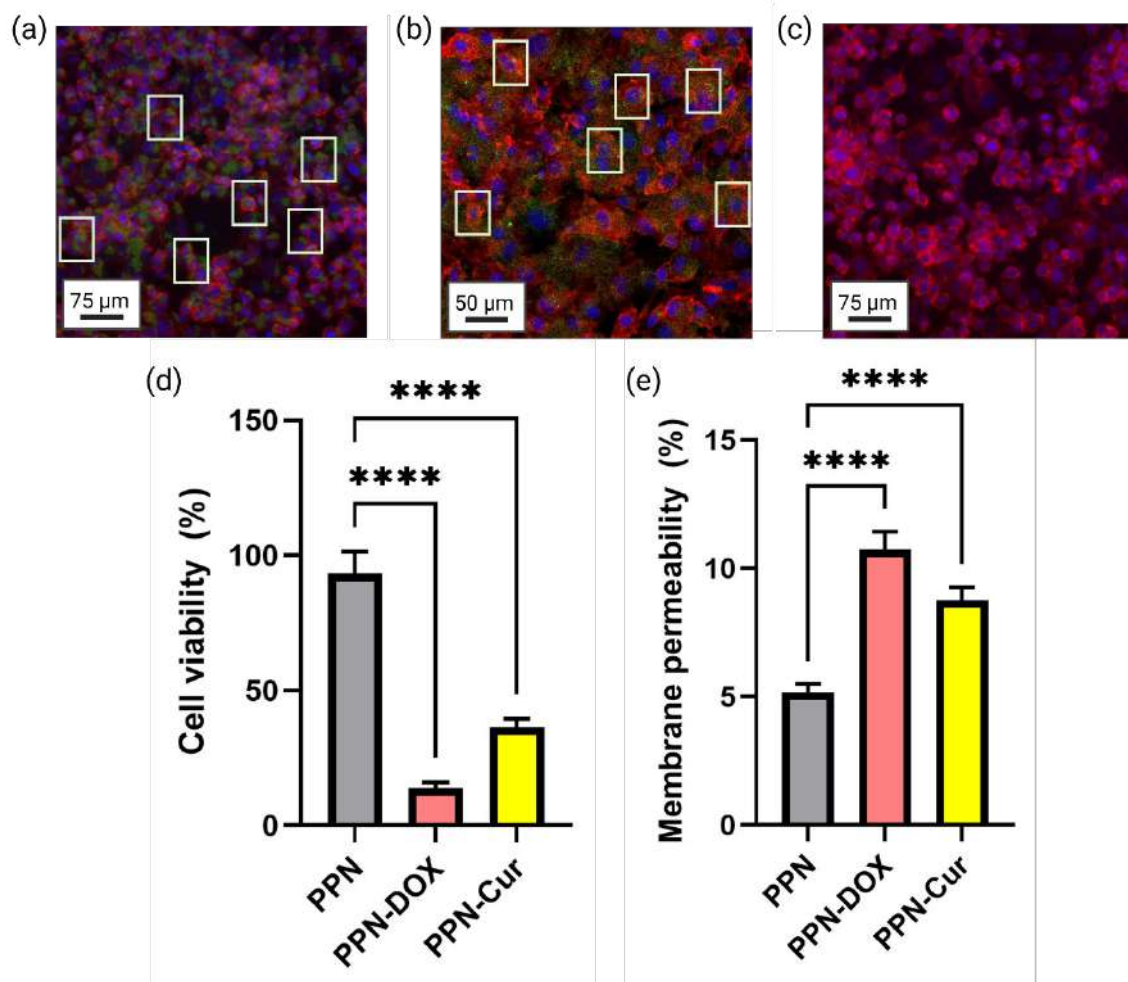


Figure 6: Payload-conjugated PPNs as drug delivery vehicles for cancer therapy. Fluorescence microscopy images of (a) PPN-Cur, (b) PPN-DOX, and (c) unconjugated PPN control samples dosed in MDA-MB-231 breast cancer cells for 24 h. (d) Alamar blue cytotoxicity assay and (e) LDH leakage assay. All data are presented as mean $\pm$ SD ($n = 3$). Statistical significance is denoted as follows: (****) $P < 0.0001$.

The successful internalisation of the payload-conjugated PPN translated to lower cell viabilities and higher membrane permeability of MDA-MB-231 cells as determined by Alamar Blue cytotoxicity assay and lactate dehydrogenase (LDH) leakage assay, respectively. Specifically, the cell viability and

proliferation of the breast cancer cells significantly decreased ($P < 0.0001$) from $93.91 \pm 8.39\%$ for the unconjugated PPN to $14.02 \pm 2.22\%$ and $35.85 \pm 2.70\%$ for PPN-DOX and PPN-Cur, respectively (Figure 6d). The lower cell viability indicates cytotoxicity of both PPN-DOX and PPN-Cur towards MDA-MB-231 breast cancer cells. In addition, LDH leakage assay reveals an increase in membrane permeability upon introducing the cytotoxic payload-conjugated PPNs. LDH is a soluble enzyme found in the cytosol and is released into the cell culture medium once the cell membrane is ruptured. Membrane permeability, which has baseline levels at $5.17 \pm 0.33\%$ for the control PPN, spiked to $10.75 \pm 0.68\%$ for PPN-DOX, and to $8.76 \pm 0.51\%$ for PPN-Cur (Figure 6e). These LDH leakage assay results corroborate with the cell internalisation and cytotoxicity studies, highlighting the potential of PPNs as viable nanoplateforms for drug delivery applications.

These findings establish the therapeutic potential of PPNs as an integrated nanoplateform capable of targeted delivery and cellular disruption, supporting their application in cancer nanomedicine. Beyond cancer therapy, these PPNs can be functionalised with other biomolecules for treating other diseases, sensitive biosensing, and cellular imaging applications.

Conclusion

This work demonstrates the promise of PPNs as multifunctional nanoplateforms that unite diagnostic imaging and therapeutic delivery in a single system. Through a one-step, chemical-free plasma process, diverse biomolecules were covalently conjugated onto PPN surfaces without the need for toxic solvents, linkers, or complex multi-step chemistry. Fluorophore-functionalised PPNs enabled real-time tracking of cellular uptake, while drug-conjugated PPNs achieved profound cytotoxic effects against triple-negative breast cancer cells, validating their therapeutic efficacy.

The sustainable and scalable plasma-based approach addresses long-standing barriers in nanomedicine by providing a green, modular, and clinically translatable strategy for cancer treatment. By integrating diagnosis and therapy into one adaptable carrier, PPNs represent not only a scientific advance but also a prototype with humanity at its core: a technology designed to transform cancer care while reducing environmental and manufacturing burdens.

Acknowledgements

Behnam Akhavan acknowledges the support of the Australian Research Council (ARC) through the DECRA program (DE210100662). The authors acknowledge the Sydney Nano Institute and the Hunter Medical Research Institute through the Precision Medicine Research Program. Elmer S. Austria Jr. acknowledges the support of the Faculty of Engineering Research Scholarship and the Career Advancement Award (PR4423/PR4424) from the University of Sydney. The authors would like to thank Dr. Ken Aldren S. Usman (Deakin University) and Prof. Joselito M. Razal (Deakin University) for access to the microscopy hub, and Prof. Elizabeth J. New (the University of Sydney) for generously providing the Rho1 fluorophore and access to confocal microscopy facilities. Austria and Akhavan also extend their sincere gratitude to Prof. Marcela M. M. Bilek (the University of Sydney) for her invaluable

guidance and mentorship. The authors gratefully acknowledge the facilities, technical, and scientific support provided by Sydney Microscopy and Microanalysis, the University of Sydney node of Microscopy Australia, and by Sydney Analytical, a core research facility at the University of Sydney.

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Chapter 2

An Affordable Brainwave Reader to Help People with Motor Neurone Disease (MND) Communicate via Thoughts Using Novel AI Technology

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Abstract

Brain-computer interface (BCI) technology provides a method of communication for people whose motor neurons are impaired and unable to communicate but their cognition is preserved as in the case of motor neurone disease (MND). This paper reports the design and evaluation of a low-cost, non-invasive EEG-based BCI prototype that could provide families and health carers with a solution to effectively communicate with a person with physical and speech disability, such as completely locked-in-syndrome (CLIS). As a low-cost technology, it could also support patients in developing countries where other technologies might be unaffordable. The first developed system, named Responsive Assisted Dialogue version 1 (RAD1), recognises two mental imagery states and maps them to simple communication outputs, this to support ‘yes/no’ or ‘option1/option2’ communication to provide patients with a communication tool. The system employs three EEG electrodes across the head and data are processed using artificial intelligence (AI) and a modified version of the novel Automated Sensory and Signal Processing (ASPS) approach. The extracted sensory features are fed into a Feed Forward Neural Network (FFNN) classifier. The results, using healthy volunteers and a volunteer with MND, indicate a very positive result to identify key communication messages via imaginations.

Keywords: *Artificial Intelligence, Brain, EEG, BCI, ANN, ALS, MND, CLIS*

Introduction

Brain-computer interface (BCI) enables information transfer directly from neural activity by sensing and decoding brain signals. This paradigm is particularly relevant for motor neurone disease (MND) patients, where progressive degeneration of motor neurones disrupts voluntary movement, but capacities such as imagination and memory often remain intact. In amyotrophic lateral sclerosis (ALS), a major subtype of MND, BCIs have been shown to preserve communication even in severe disability or completely locked-in syndrome (CLIS)¹. Al-Habaibeh (2025) has highlighted in his recent article the future of chip implants for Brain-Computer Interface where invasive technologies are being tested with

¹Ioulietta Lazarou et al., “EEG-Based Brain-Computer Interfaces for Communication and Rehabilitation of People with Motor Impairment: A Novel Approach of the 21st Century,” *Frontiers in Human Neuroscience* 12, no. 14 (January 31, 2018), <https://doi.org/10.3389/fnhum.2018.00014>

implants directly placed on the brain's surface². Such invasive technologies require sophisticated medical and surgical procedures hence making it an expensive option.

Among numerous non-invasive brain imaging systems, electroencephalography (EEG) is widely used due to high temporal resolution, non-invasive operation, portability, and affordability. EEG contributes substantially to diagnosis and to biomedical engineering research and underpins many BCI approaches³. Patients with ALS typically have limited communication options: eye-activity systems (e.g., gaze trackers) can demand continuous effort, induce fatigue, and become impractical in supine positions; in contrast, cognitive-activity BCIs (e.g., motor imagery) offer greater comfort and flexibility⁴. This study presents an affordable EEG-BCI that detects two distinct mental imagery states and translates them into binary outputs for basic communication (e.g., "Yes/No"). The objectives were to: (i) design a low-cost EEG prototype; (ii) implement it using cost-effective, reliable components; (iii) acquire signals under a controlled protocol; (iv) process and analyse signals within an AI and ASPS signal analysis framework; (v) deliver a simple graphical user interface (GUI) software for acquisition, processing, and communication; and (vi) evaluate system performance. The emphasis is on simplicity, reproducibility, and feasibility in resource-constrained settings. To overcome the challenges of sensory feature extraction and the integration with AI, Al-Habaibeh and Gindy (2000) proposed the ASPS approach, which automates feature discovery and selection from sensory signals⁵. Majumdar et al. (2023) investigated the ASPS approach in brain signal processing and has demonstrated high accuracy to recognise different number of imaginations⁶. Figure 1 presents the block diagram of the modified ASPS approach for brain signal processing.

The ASPS approach for BCI technology is based on extracting the EEG signals as in Figure 1A and processing it using a wide range of signal processing methods (Figure 1B) to produce sensory characteristic features (SCFs) that are organised for each sensor and signal processing method in a 3D matrix (Figure 1C). Following that, the sensitivity or dependency of each SCF on the imagination is organised in an association matrix, (Figure 1D). The behaviour of SCFs is combined to create unique patterns (Figure 1E). The AI system is trained on the relationship between a group of SCFs and the

²A. Al-Habaibeh and N. Gindy, "A New Approach for Systematic Design of Condition Monitoring Systems for Milling Processes," *Journal of Materials Processing Technology* 107, no. 1–3 (November 1, 2000): 243–51, [https://doi.org/10.1016/s0924-0136\(00\)00718-4](https://doi.org/10.1016/s0924-0136(00)00718-4)

³Katarzyna Blinowska and Piotr Durka, "Electroencephalography (EEG)," *Wiley Encyclopedia of Biomedical Engineering*, April 4, 2006, <https://doi.org/10.1002/9780471740360.ebs0418>

⁴Liliana García et al., "A Comparison of a Brain-Computer Interface and an Eye Tracker: Is There a More Appropriate Technology for Controlling a Virtual Keyboard in an ALS Patient?" in *Lecture Notes in Computer Science*, 2017, 464–73, https://doi.org/10.1007/978-3-319-59147-6_40

⁵Al-Habaibeh and Gindy, 2000, "A New Approach for Systematic Design of Condition Monitoring Systems for Milling Processes," *Journal of Materials Processing Technology*, 107, pp. 243–251.

⁶Sharmila Majumdar et al., "A Novel Approach for Communicating with Patients Suffering from Completely Locked-in-syndrome (CLIS) via Thoughts: Brain Computer Interface System Using EEG Signals and Artificial Intelligence," *Neuroscience Informatics* 3, no. 2 (March 21, 2023): 100126, <https://doi.org/10.1016/j.neuri.2023.100126>

possible imaginations or thoughts (Figure 1G). Following that, the AI system (neural networks) is utilised to classify the AI system in recognising the imagination of the patient (Figure 1H). This present work aims to develop a non-invasive and affordable EEG-BCI system, named RAD1, that leverages low-cost hardware and ASPS-style feature automation and AI integration to deliver practical communication tool for MND patients.

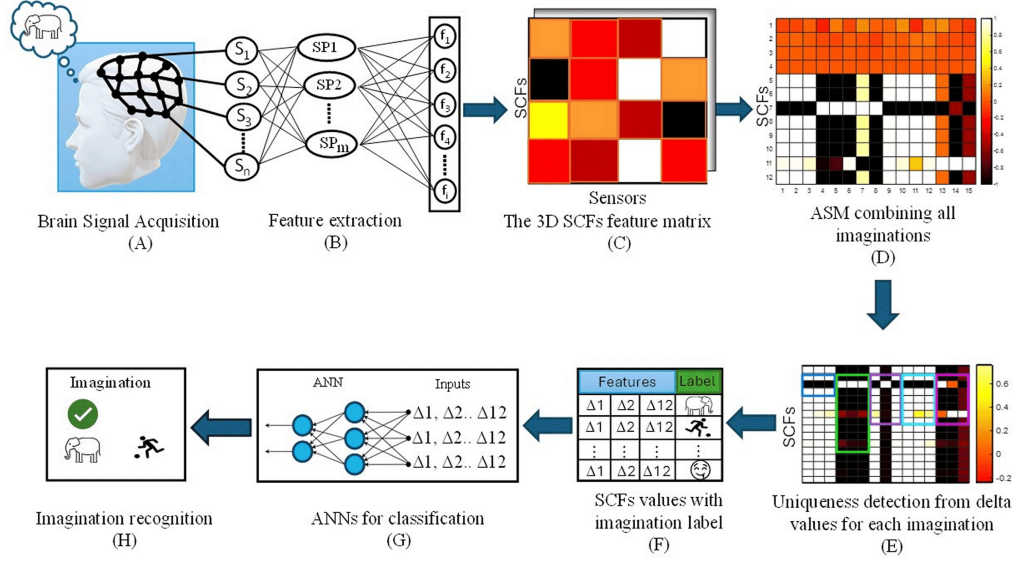


Figure 1: The block diagram of the ASPS approach applied to brain signal processing.

Methodology

The RAD1 prototype was developed to combine the AI-ASPS algorithm with a low-cost hardware and computer interface to test in real-time communication via thoughts using EEG signals. A low-cost EEG board for each electrode provided the analogue EEG input and output, where the three signals are interfaced to a data acquisition board for data digitalisation and analysis using Matlab software. Figure 2 illustrates the schematic diagram of the EEG-BCI used for data acquisition.

All components were housed in a compact enclosure with a high-speed USB port for data transfer and a 3.5 mm jack for sensor connections, improving safety and repeatability. Figure 3 presents the updated system, with Figure 3A showing the top view and Figure 3B presenting the side view of the newly designed EEG-BCI RAD1 prototype.

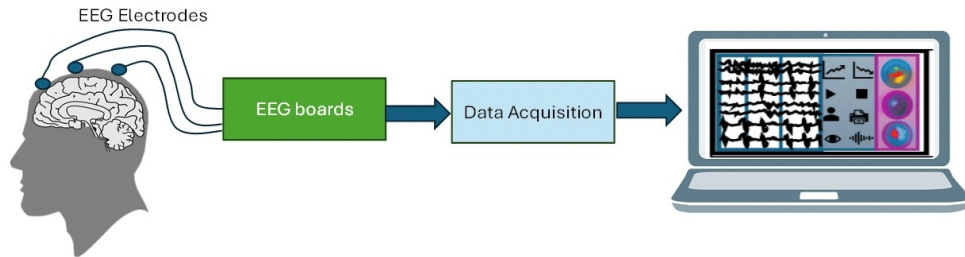
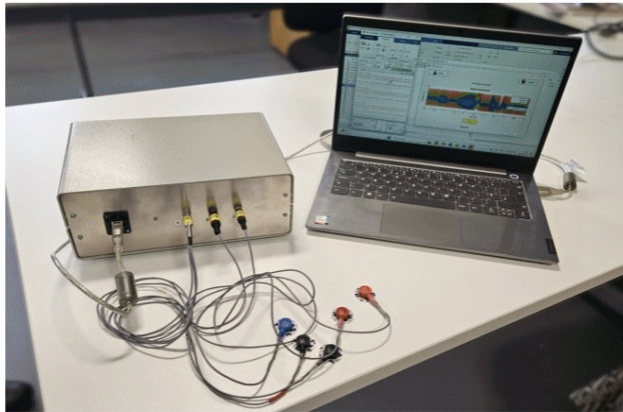
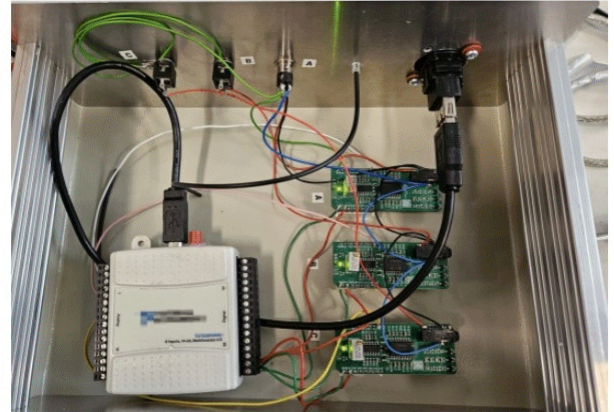


Figure 2: A schematic diagram of EEG-BCI for signal acquisition.



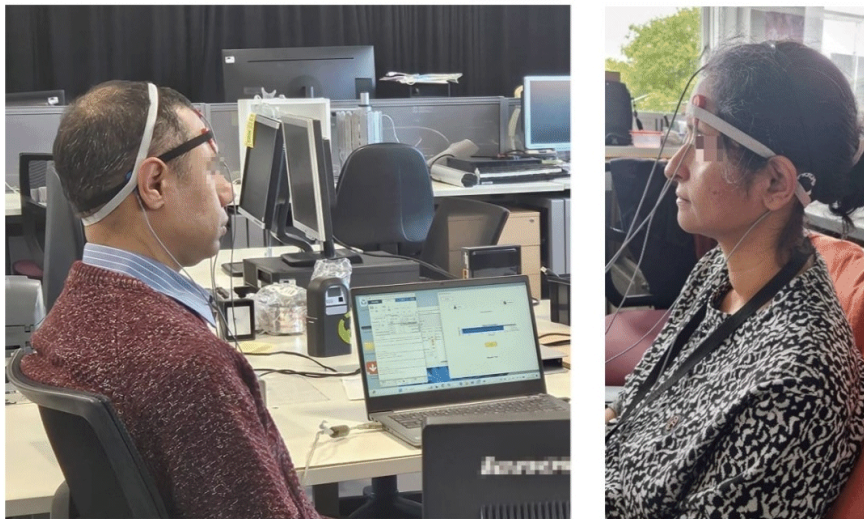
(A) The novel low-cost RAD1 prototype



(B) Top view of the RAD1 prototype

Figure 3: The newly developed EEG-BCI RAD1 prototype.

The electrode locations are selected to facilitate ease of placement, consistency, and patient comfort, while also aligning with optimal positions that provide EEG signals with unique signatures for the system (Figure 4).

**Figure 4:** Signal acquisition during the testing of the newly developed EEG-BCI RAD1 prototype.

Two distinct mental tasks (imagination) were selected from a large portfolio of imaginations from the background research: (i) imagining seeing an elephant and (ii) imagining kicking a football. Each trial began with a relaxation stage to establish baseline activity and reduce carry-over effects, followed by 5 seconds of sustained imagery on verbal instruction. Volunteers and the patient were reminded to minimise jaw tension, eye blinks and body movement to limit artefacts. Signals were acquired simultaneously from the three sensors as shown in Figure 4.

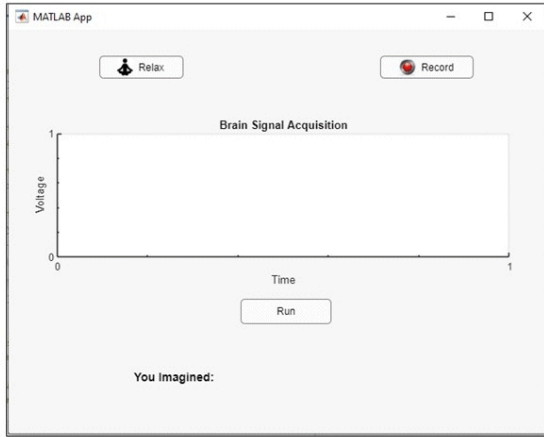
To reduce computing demands and reduce cost, processing was focussed on frequency-domain characterisation using the ASPS approach with AI integration. For each channel, a fast Fourier transform (FFT) was computed and its magnitude spectrum partitioned into five frequency regions, guided by inspection of representative spectra. For each region, four statistical functions: mean, standard deviation, variance, and maximum, were computed, yielding 20 SCFs per channel due to

dividing the frequency signal to five sections (bands). The definitions and equations are presented in Table 1. The difference in SCFs values (Δ) helped suppressing common-mode trends and reduce noise, including the persistent 50 Hz component observed in environmental conditions from interference. The resulting features were combined and used to create a unique signature for each imagination.

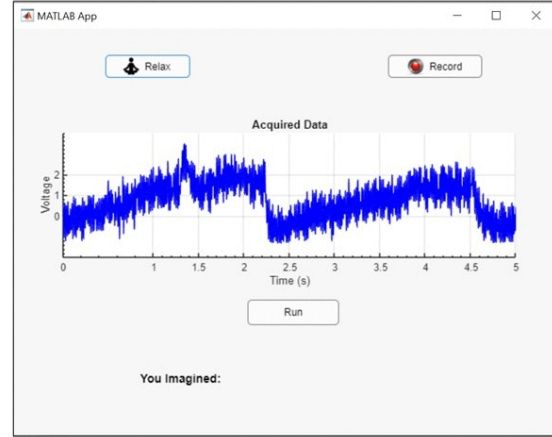
Table 1: Definitions and equations of the four selected statistical functions to process FFT segments.

Index	Definition	Equation
1	Mean	$E_1 = \frac{1}{n} \sum_{i=1}^n x_i$
2	Standard deviation	$E_2 = \sqrt{\frac{\sum_{i=1}^n (x_i - E_1)^2}{N}}$
3	Variance	$E_3 = \frac{\sum_{i=1}^n (x_i - E_1)^2}{N}$
4	Max	$E_4 = \max(x_i)$

A single-layer FFNN neural network received the SCFs as inputs to produce a classification output as a binary decision. To probe model capacity and stability, hidden-layer sizes from 1 to 120 neurons were evaluated. For each size, the network was trained and tested 50 times with random initialisations, and both maximum and average accuracies were recorded. A MATLAB GUI coordinated acquisition, visualisation, and output. Real-time plots displayed scrolling raw EEG and corresponding FFT spectra; a status panel reported the current classification and confidence. For demonstration, the binary decision was mapped to on-screen messages that could be connected to communication outputs (Figure 5).



The Graphical User Interface (GUI)
before recording
(A)



The Graphical User Interface (GUI)
after recording
(B)

Figure 5: The application view (A) before recording and (B) after recording.

The "Run" button activates the signal processing method in the background, classifies the signals, and displays the communication output on the screen. This application is designed with bespoke manner, where the internal FFNN model is trained offline for individual subjects. The system processes real-time data from the subject and generates the corresponding communication output based on the trained model. Hence providing real-time communication via thoughts.

Results and Discussion

The FFT segments are determined by considering the FFT outcomes of the raw signals, as illustrated in Figure 6, which displays (A) the raw signal and (B) the corresponding FFT outcome.

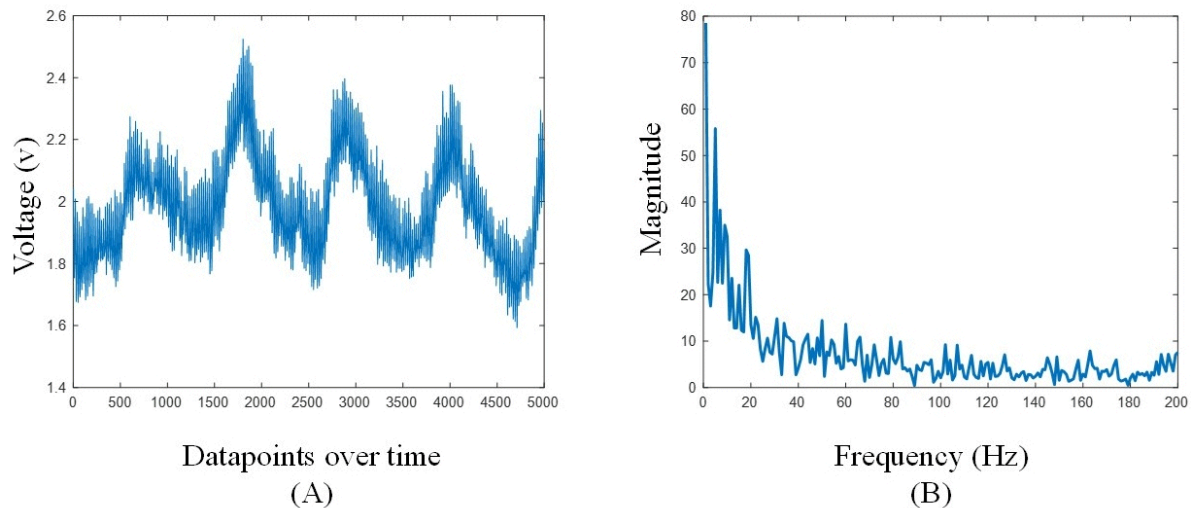


Figure 6: Signal visualisation (A) of raw signal recording using EEG-BCI RAD1 prototype and (B) the associated FFT plot.

Figure 7 illustrates an example of the performance recorded over 50 runs, with a dotted line representing the mean performance across these runs. The FFT-generated SCFs yielded a maximum accuracy of 100% and an average of 79% across 50 runs.

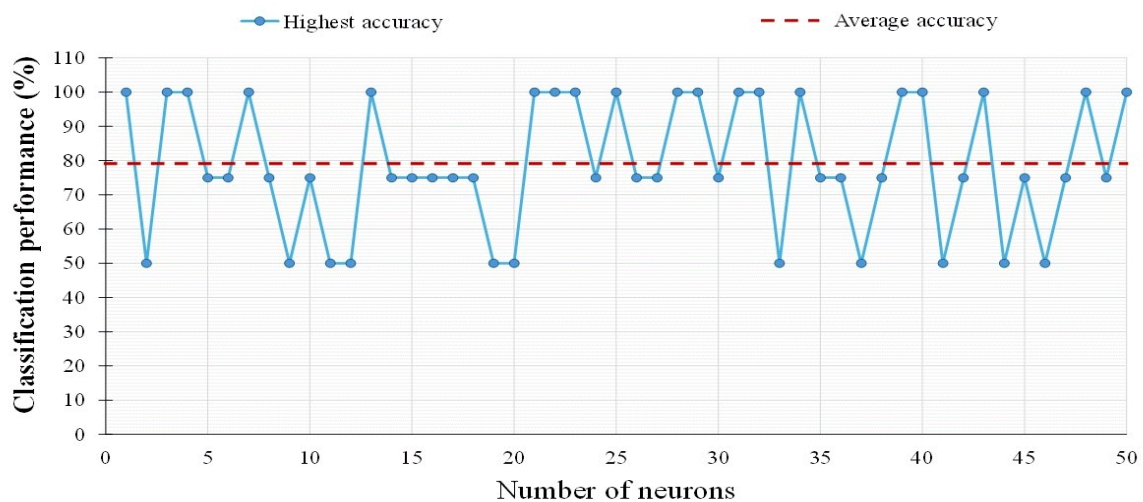


Figure 7: Classification performance of EEG-BCI RAD1 prototype using the ASPS approach and neural networks using five-section frequency domain generated SCFs.

The prototype captured clear signals from three sensors and displayed them in real time. Using the FFT features per segment (band), the FFNN achieved frequent 75% accuracies across hidden-layer sizes, with multiple instances of 100%. From the hardware point of view, the electrodes were easy to place, comfortable, and yielded reliable accuracies. The GUI streamlined the process from calibration to classification, while the enclosed hardware assembly simplified sensor uses and minimised error. Together, the system demonstrated practical end-to-end feasibility for thought-based communication.

The results show that the proposed non-invasive and affordable EEG-BCI can separate two mental imagery states or thoughts with reliability for communication purposes. The SCF features from five spectral bands captured discriminative patterns with low dimensionality, enabling the neural network to learn effectively from concise data. Performance averaged 79%, with 100% success with rounding the results to binary format, hence reflecting stable spectral differences between the two imaginations.

Conclusion

This paper presented the design and evaluation of an affordable novel EEG-BCI RAD1 prototype tailored to support communication via thoughts for MND patients. Using three EEG electrodes and 1 kHz sampling rate, ASPS-guided FFT feature extraction and an FFNN neural network, the system reliably discriminated between two mental imagery states or thoughts. A high accuracy of 100% for rounded results were achieved. This proposed technology demonstrates the feasibility of low-cost, non-invasive thought-driven EEG communication using AI. Future work will include further noise reduction and additional SCFs with broader validation on diverse users.

Acknowledgement

The authors would like to thank all volunteers for supporting this work. Special thanks to Nottingham Trent University for funding this work via the Medical Technologies and Advanced Materials Theme (Grant number 01EGI-RD066) and the PhD research sponsorship from School of Architecture, Design and the Built Environment.

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Artificial Intelligence.” *Neuroscience Informatics* 3, no. 2 (Mar 2023): 100126. <https://doi.org/10.1016/j.neuri.2023.100126>

Chapter 3

IA Multimodal Platform for Objective Pain Measurement

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Abstract

Pain remains a complex and pervasive clinical challenge, affecting patient quality of life and healthcare systems worldwide. Current assessments rely on subjective self-reports, which are limited by perception, communication barriers, and emotional factors. Recent advances suggest physiological biomarkers, such as electrodermal activity and heart rate variability, can serve as objective indicators by reflecting autonomic responses. However, an integrated, multimodal system combining biomedical signals from wearable devices for real-time objective pain detection has yet to be fully developed. Building on this, our project's focused on building an AI-powered pain index that complements or replaces subjective scales, enabling better clinical decisions especially for infants and those unable to communicate, thus advancing precision pain medicine and improving patient outcomes.

Keywords: *Personalised medicine, Biomedical data, AI-modelling, Pain index*

Introduction

Pain remains a complex and widespread challenge in medicine, affecting quality of life and healthcare resources globally. Defined by ICD-11¹, pain is classified as acute or chronic, with acute pain warning of injury and resolving within months, while chronic persists beyond healing². Whether chronic or acute we still understand very little about pain, and no clear biomarkers are currently used for diagnosis or management. Current assessment methods predominantly rely on subjective self-report scales, such as the numerical rating scale (NRS) and the visual analogue scale (VAS), which are inherently limited by individual perception (communication barriers/emotional states), especially in populations unable to communicate, such as infants or neurological patients³.

¹Joanna R. Rozisky et al., "Modified Non-invasive Brain Stimulation in Fibromyalgia." "Modified Non-invasive Brain Stimulation in Fibromyalgia." *Journal of Pain and Relief* 3, no. 4 (Jan 2014): 1–7.
<https://doi.org/10.4172/2167-0846.1000149>

²Daniel S. Goldberg and Summer J. McGee, "Pain as a Global Public Health Priority," *BMC Public Health* 11, no. 770 (October 6, 2011), <https://doi.org/10.1186/1471-2458-11-770>

³R. Cowen et al., "Assessing Pain Objectively: The Use of Physiological Markers," *Anaesthesia* 70, no. 7 (2015): 828–47, <https://doi.org/10.1111/anae.13018>

Recent advances suggest that physiological biomarkers, such as electroencephalogram (EEG)⁴, electrodermal activity (EDA)⁵, heart rate variability (HRV)⁶, respiratory rate (RR)⁷, blood saturation⁸, and body temperature (T)⁹, may serve as objective indicators of pain by reflecting autonomic nervous system responses. However, an integrated system combining these signals from wearable devices remains undeveloped. Taking this into account, our initiative aims to create an AI-powered, multimodal platform that uses wearable sensors, like smartwatches, to provide real-time, objective pain assessment. This approach promises to improve diagnosis, monitoring, and pain management across diverse clinical settings. Existing studies have demonstrated correlations between individual autonomic biomarkers and pain states¹⁰⁻¹². We focus on autonomic responses and behavioural perceptions for a more accurate and robust pain index¹³ that will enable us to detect and quantify pain through smart wearables. We consider utilising smartwatches due to being among the most widely adopted wearables globally with over 200 million smartwatches being sold annually worldwide¹⁴. The current manuscript outlines our approach what has been achieved up to today and how we aim to finalise the development of our pain index platform to improve pain care.

Proposed Methodology

Phase 1: Open data sets AI modelling

We have successfully completed the first phase, including a literature review on machine learning (ML)

⁴Abeer Al-Nafjan, Hadeel Alshehri, and Mashael Aldayel, "Objective Pain Assessment Using Deep Learning Through EEG-Based Brain-Computer Interfaces," *Biology* 14, no. 2 (February 17, 2025): 210, <https://doi.org/10.3390/biology14020210>

⁵Viprali Bhatkar, Rosalind Picard, and Camilla Staahl, "Combining Electrodermal Activity With the Peak-Pain Time to Quantify Three Temporal Regions of Pain Experience," *Frontiers in Pain Research* 3, 764128 (March 23, 2022), <https://doi.org/10.3389/fpain.2022.764128>

⁶Giuseppe Forte et al., "Heart Rate Variability and Pain: A Systematic Review," *Brain Sciences* 12, no. 2 (January 24, 2022): 153, <https://doi.org/10.3390/brainsci12020153>

⁷Hassan Jafari et al., "Pain and Respiration: A Systematic Review," *Pain* 158, no. 6 (January 30, 2017): 995–1006, <https://doi.org/10.1097/j.pain.0000000000000865>

⁸Lars Ø. Høiseth et al., "Tissue Oxygen Saturation and Finger Perfusion Index in Central Hypovolemia," *Critical Care Medicine* 43, no. 4 (2015): 747–56, <https://doi.org/10.1097/ccm.0000000000000766>

⁹Alice A. Larson, José V. Pardo, and Jeffrey D. Pasley, "Review of Overlap Between Thermoregulation and Pain Modulation in Fibromyalgia," *Clinical Journal of Pain* 30, no. 6 (2014): 544–55, <https://doi.org/10.1097/ajp.0b013e3182a0e383>

¹⁰Cowen et al., "Assessing Pain Objectively: The Use of Physiological Markers."

¹¹Reed Larson and Mihaly Csikszentmihalyi, "The Experience Sampling Method." In *Flow and the Foundations of Positive Psychology*, editing by Mihaly Csikszentmihalyi. Springer, 2014.

¹²Larson, Pardo, and Pasley. "Review of Overlap Between Thermoregulation and Pain Modulation in Fibromyalgia."

¹³Brandon N Kyle and Daniel W McNeil, "Autonomic Arousal and Experimentally Induced Pain: A Critical Review of the Literature," *Pain Research and Management* 19, no. 3 (2014): 159–67, <https://doi.org/10.1155/2014/536859>

¹⁴Michael R Massoomi and Eileen M Handberg, "Increasing and Evolving Role of Smart Devices in Modern Medicine," *European Cardiology Review* 14, no. 3 (December 18, 2019): 181–86, <https://doi.org/10.15420/ecr.2019.02>

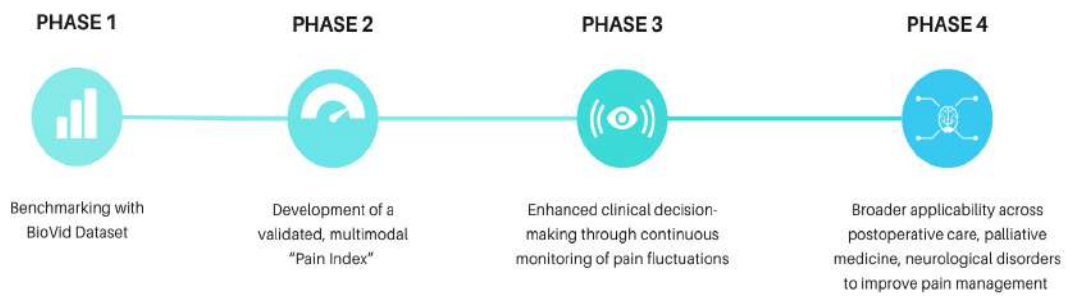


Figure 1: Illustration of the four phases in the methodology.

algorithms and convolutional neural networks (CNNs) for automated pain assessment. During this stage, we developed a preliminary model using public research data, in collaboration with the Rochester Institute of Technology Dubai. During this initial phase, we tested an AI-driven pain assessment model, which will be used in phase 2 and phase 3 of the study with real world data (healthy subjects and clinical setting). We primarily focused on two key public datasets: BioVid Heat Pain Database (Part B) and X-ITE Pain Challenge 2025 dataset that offer controlled pain stimuli and multimodal physiological data. We emphasised on biosignals data (EDA, ECG, EMG) within the datasets, excluding behavioural data which can be key to minimising the risk of false positives, with a primary focus on physiological parameters.

Phase 2: Human testing (healthy subjects)

In phase 2 we aim to evaluate the platform's ability to detect experimentally induced acute pain through cold pressor task (submerging their dominant hand in cold water). Key objectives include optimising sensor integration, refining data collection protocols, and conducting initial model training in healthy subjects, aged 18–60 of all genders. They will be asked to wear a smartwatch, and their pain levels will be assessed through an eVAS, with the pain intensities categorised into four levels. This serves as a validation for the development of the AI model.

Phase 3: Clinical evaluation (acute pain model)

This phase involves validating the platform in real-world clinical settings by monitoring postoperative patients during their recovery. The goal is to assess how the pain index correlates with patient perceptions and the overall recovery process, evaluating the real-time features of our pain index and its impact in immediate clinical decisions and personalised pain management.

Phase 4: Adaptation for chronic pain assessment

This last phase aims to translate the acute pain index to evaluate and monitor patients suffering from chronic pain conditions, such as cancer-related pain. Cancer related pain is an appropriate model to

assess complex acute and chronic pain simultaneously, due to its complex nature¹⁵. Our objective is to investigate how to translate what is observed in acute pain, into chronic pain modelling, considering that chronic pain often involves blunted or dysregulated physiological responses. This will enable us to determine whether the pain index can also become a reliable tool to help objectify the complex autonomic dynamics associated with chronic pain states.

Results

Benchmarking with the BioVid dataset

We evaluated standard ML pipelines such as AdaBoost, XGBoost, and Random Forest on the BioVid dataset to have an insight on their performance in classifying pain levels based on engineered signal features.

Participation in the X-ITE Pain Challenge 2025

To widen our understanding on pain data, we participated in the X-ITE Challenge 2025, which addressed the classification of LOW and MODERATE pain levels. We focused on analysing the challenges in pain classifications. This involvement helped us assess the behaviour of XGBoost and LightGBM models.

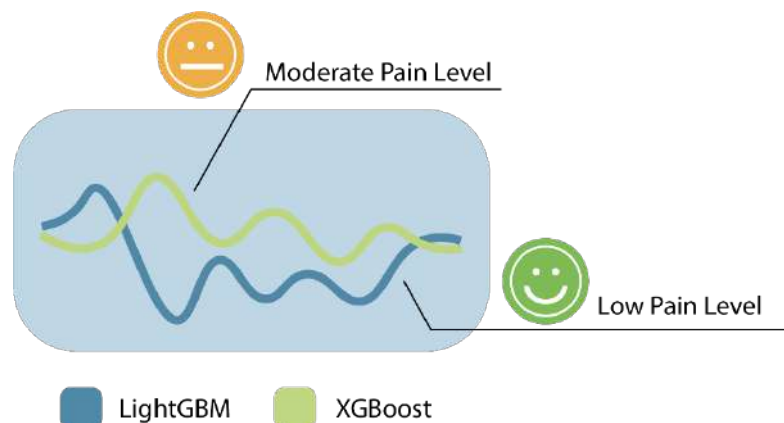


Figure 2: Representation of pain model.

Discussion

Random Forest achieved the highest accuracy (98.63%) in our initial analysis using only noise reduction on the BioVid dataset. After incorporating modality-specific feature extraction, the best models shifted to AdaBoost for ECG (85.8%), XGBoost for EMG (85.0%), and AdaBoost for GSR (76.9%). This performance change underscores the value of physiologically meaningful, modality-tailored features, despite the overall drop in accuracy. While only cross-validation accuracy is reported here, future work will include additional metrics such as F1-score and AUC for a more comprehensive evaluation.

¹⁵Rianne De Wit et al., “Assessment of Pain Cognitions in Cancer Patients With Chronic Pain,” *Journal of Pain and Symptom Management* 22, no. 5 (November 1, 2001): 911–24, [https://doi.org/10.1016/s0885-3924\(01\)00354-2](https://doi.org/10.1016/s0885-3924(01)00354-2)

Clinical Considerations

In Phases 2, 3, and 4 we anticipate the following outcomes:

- Firstly, to be able to develop a validated, multimodal “pain index” that surpasses subjective scales in reliability and objectivity.
- Second, to enhance clinical decision-making through continuous monitoring of pain fluctuations. We envision a broader applicability across settings from postoperative care, palliative medicine to neurological disorders, improving pain management in underserved populations. Wearable technology will contribute to the advancement of personalized medicine, with data-driven insights guiding tailored interventions.

Conclusion

This overview aims to lay the foundation for an objective, multimodal pain index platform based on integrating wearable sensors, AI, and robust clinical validations. This innovation would enable continuous and objective pain assessment, especially for those unable to communicate, transforming pain care worldwide and improving quality of life.

Acknowledgements

This project is funded by Dubai Future Foundation – RDI Program Grant: 2025/DRDI0173.

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Chapter 4

Equira™ (VoxelPHITS): Democratising Precision Radiopharmaceutical Therapy for Global Cancer Care

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Abstract

Radiopharmaceutical therapy is an essential option for cancers such as hepatocellular carcinoma, metastatic prostate cancer, and neuroendocrine tumours, delivering radiation internally via targeted radiolabelled compounds. Yet, most patients are still treated with empirical, fixed-dose protocols, with limited knowledge of the absorbed dose to tumours and organs-at-risk (OARs), driving variability in outcomes and avoidable toxicity.

Equira™, developed from the VoxelPHITS platform, offers a practical, scalable solution to personalised dosimetry. The open-source, vendor-neutral software converts standard CT (anatomy/tissue density) and SPECT/PET (radioactivity) into patient-specific 3D dose maps using Monte Carlo simulation and pre-computed dose-voxel kernels for speed. It accepts routine DICOM inputs, runs on Windows and Linux, and is designed for deployment in both high- and low-resource settings without specialised infrastructure. Outputs include isodose overlays, dose-volume histograms (DVHs, and tabulated dose metrics (e.g. D_{mean} , D_{95} , V_x) suitable for pre-treatment planning and post-therapy verification.

By aligning treatment decisions with measured dose rather than surrogates, Equira™ can improve safety, efficacy, and equity in radionuclide therapy. Its development supports a broader shift toward accessible precision medicine, enabling centres worldwide to deliver “the right dose, first time” and to standardise protocol optimisation with interpretable task-based metrics.

Keywords: *Radiopharmaceutical therapy, Voxel-based dosimetry, Monte Carlo simulation, Personalised dosing, VoxelPHITS*

Introduction

Precision medicine in radiopharmaceutical therapy requires not only locating tumours but also quantifying the absorbed dose to tumours and organs-at-risk (OARs). For radionuclides such as Yttrium-90 (Y-90), Samarium-153 (Sm-153), Lutetium-177 (Lu-177), and Holmium-166 (Ho-166),

internal dosimetry is essential to balance efficacy against toxicity¹⁻⁷. Yet, according to the European Association of Nuclear Medicine (EANM) Dosimetry Committee surveys, about 70% of radiopharmaceutical therapies worldwide still use empirical dosing, contributing to variability in outcomes and elevated toxicity risks⁸⁻¹⁰. A key barrier is the limited availability of practical, accessible tools for personalised dosimetry¹¹.

Equira™, built on the modular VoxelPHITS platform, addresses this gap by transforming routine CT (anatomy/tissue density) and SPECT/PET (radioactivity) into patient-specific 3D dose maps. Leveraging the PHITS Monte Carlo software with pre-computed dose-voxel kernels, it delivers high-fidelity voxel-based dosimetry on standard Windows/Linux workstations, avoiding the need for specialised computing infrastructure or advanced physics expertise¹². Dosimetry outputs, such as isodose overlays, DVHs, and tabulated dose metrics, are integrated into familiar clinical workflow for pre-treatment planning and post-therapy verification.

By providing an open, vendor-neutral, and easily deployable platform, Equira™ offers a practical route to personalised dosing across both high- and low-resource settings.

Results and Discussion

Platform capability and robustness

Equira™ is designed to be easily accessible, adaptable, and technically robust. It runs on Windows or Linux, accepts standard Digital Imaging and Communications in Medicine (DICOM) inputs from any imaging modalities, and installs locally within hospital networks to comply with patient data privacy requirements while still allowing secure remote updates. A modular framework supports multiple

¹C. Chiesa et al., “Radioembolization of Hepatocarcinoma with (⁹⁰Y Glass Microspheres,” *European Journal of Nuclear Medicine and Molecular Imaging* 42, no. 11 (2015): 1718–38.

²U. Garske-Román et al., “Prospective Observational Study of 177Lu-DOTA-Octreotate Therapy,” *European Journal of Nuclear Medicine and Molecular Imaging* 45, no. 6 (2018): 970–88.

³M. Del Prete et al., “Personalized 177Lu-Octreotate Therapy: P-PRRT Trial,” *European Journal of Nuclear Medicine and Molecular Imaging* 46, no. 3 (2019): 728–42.

⁴A. Sundlöv et al., “Individualized 177Lu-DOTATATE Treatment of NET,” *European Journal of Nuclear Medicine and Molecular Imaging* 49, no. 11 (2022): 3830–40.

⁵E. Garin et al., “DOSISPHERE-01 Trial,” *The Lancet Gastroenterology & Hepatology* 6, no. 1 (2021): 17–29.

⁶F. Cicone et al., “Dosimetric Approaches in Radioimmunotherapy,” *Seminars in Nuclear Medicine* 52, no. 2 (2022): 191–214.

⁷C. Kratochwil et al., “EANM/SNMMI 177Lu PSMA RLT Guideline,” *European Journal of Nuclear Medicine and Molecular Imaging* 50, no. 8 (2023): 2830–45.

⁸F. Giammarile et al., “EANM Dosimetry Committee Guidance,” *European Journal of Nuclear Medicine and Molecular Imaging* 48, no. 4 (2021): 1136–50.

⁹M. Sandström et al., “Individualised Dosimetry with 177Lu-DOTATATE,” *European Journal of Nuclear Medicine and Molecular Imaging* 44 (2017): 1480–89.

¹⁰T. Finazzi et al., “Dosimetry in Molecular Radiotherapy: European Survey,” *European Journal of Nuclear Medicine and Molecular Imaging* 49, no. 5 (2022): 1630–39.

¹¹IAEA, “Theranostics: Combining Diagnosis and Treatment,” 2025, <https://www.iaea.org>.

¹²OECD NEA, “PHITS Voxel Training Materials,” 2025, <https://git.oecd-nea.org/phits/package/phits-lecture>.

radionuclides, voxel sizes, and tissue models. Built with open-source tools such as Python and FORTRAN on the VoxelPHITS core, the platform reduces dependence on costly commercial software and supports long-term scalability and maintainability. Figure 1 shows the overview of the Equira™ workflow.

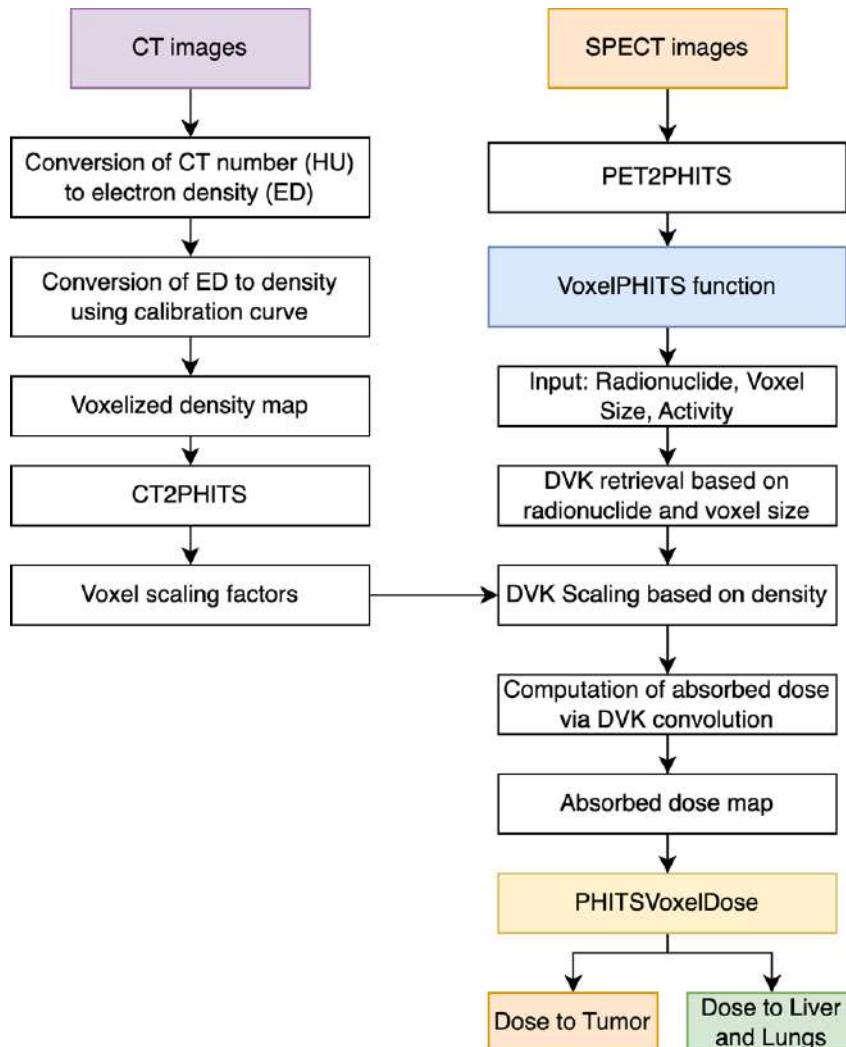


Figure 1: Overview of VoxelPHITS workflow.

Clinical utility

Equira™ quantifies absorbed dose to tumours and OARs, improving therapeutic confidence for both pre-treatment planning (to verify target coverage and OAR sparing) and post-therapy verification (to evaluate delivered dose). This aligns with modern theranostics, integrating imaging and therapy to enable patient-specific decision-making. Figure 2 illustrates a Y-90 selective internal radiation therapy (SIRT) case with baseline imaging, isodose mapping, follow-up response, and DVHs of a liver metastasis patient. Figure 3 shows multi-planar dose map visualisations generated by Equira™.

Implementation considerations and adoption

To support rapid adoption across diverse centres, Equira™ emphasises usability and trust: an intuitive interface requiring minimal training; colour-coded dose maps and location options for international

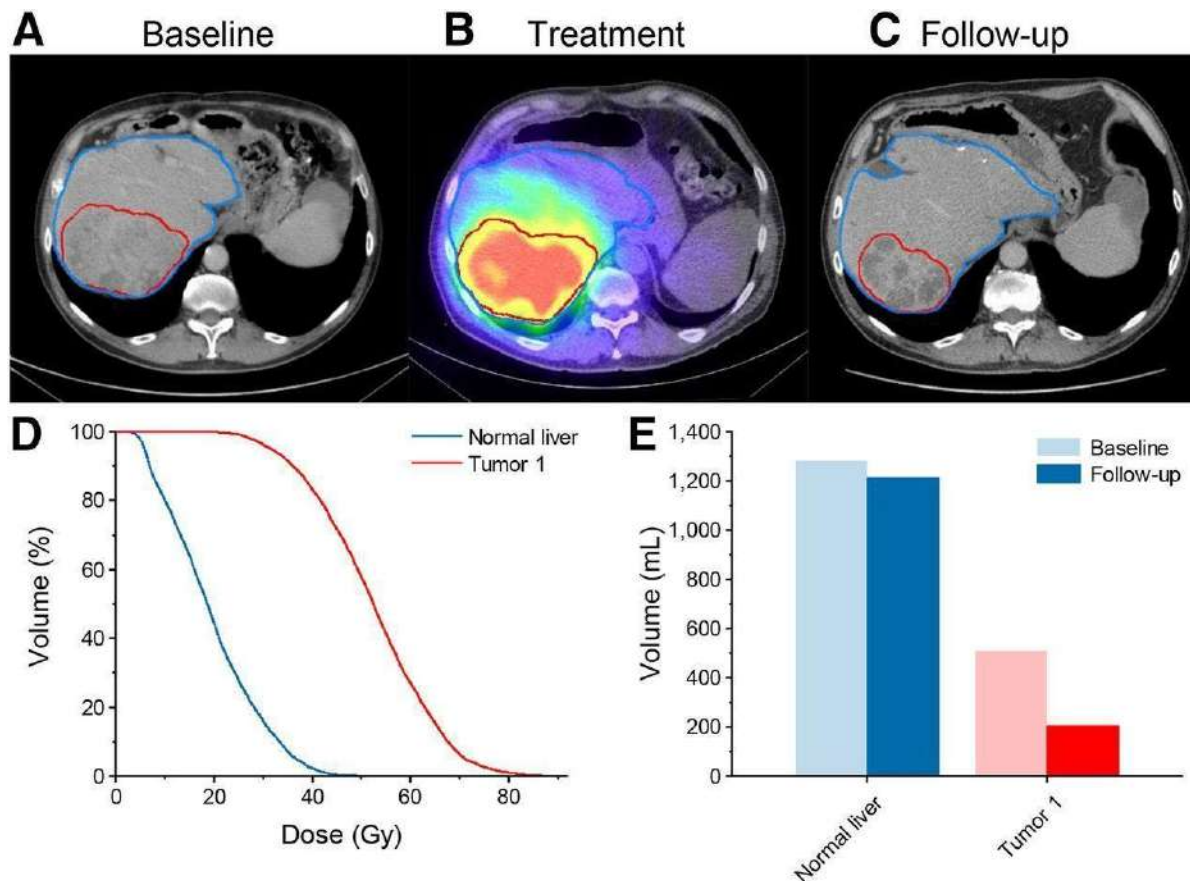


Figure 2: Personalised dosimetry for Y-90 selective internal radiation therapy (SIRT) of liver tumours. (A) Baseline CT prior to SIRT. (B) SPECT/CT with overlaid dose map demonstrating tumour and normal liver dose distribution. (C) Follow-up CT acquired at 80 days post-SIRT, revealing significant shrinkage of tumour. (D) Dose-volume histogram (DVH) for tumour and normal liver. (E) Volumetric response analysis. (Adapted from Abbott et al.¹³).

use; and commercial-grade packaging (documentation, verification cases, and user support) even though the software is open-source.

A sustainable deployment model is proposed: sites manage local installation and data control, while receiving secure online updates. A central support hub provides training materials, FAQs, peer discussion forums, and regular online training to encourage standardised practice and shared learning. Engagement with key opinion leaders (KOLs) will further strengthen credibility and accelerate clinical implementation.

Sustainability and governance

The project operates under a not-for-profit model supported by institutional partnerships and research grants, aligning the platform with global health-equity goals. Governance includes visioned radionuclide libraries, checksum-verified builds, and a minimal QA set (phantom cases, periodic checks) to ensure consistent performance across sites.

¹³E. M. Abbott et al., “The Impact of Radiobiologically Informed Dose Prescription on the Clinical Benefit of 90Y SIRT in Colorectal Cancer Patients,” *JNM* 61, no. 11 (2020): 1658–64.

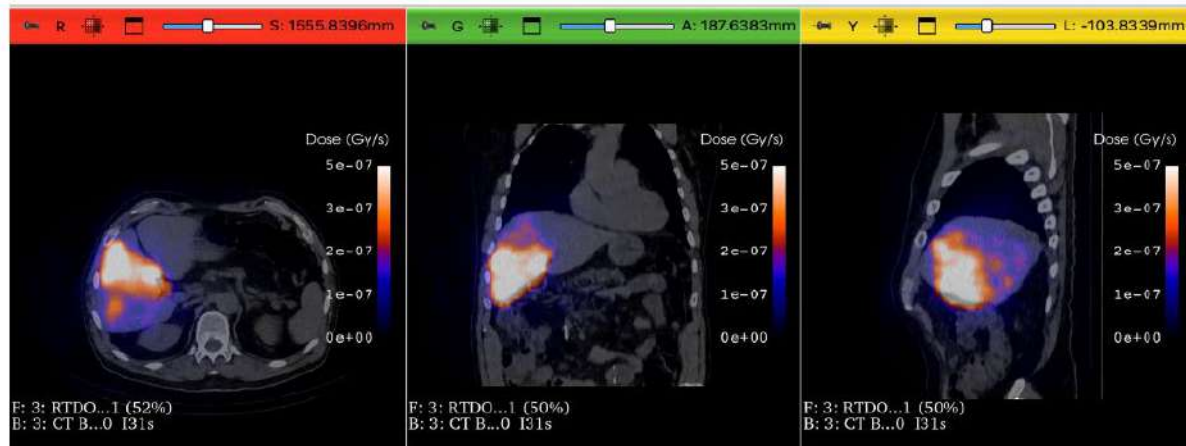


Figure 3: Cross sectional (axial, coronal and sagittal) views of a Y-90 SIRT 3D dose maps produced in Equira™.

Roadmap

Planned enhancements include AI-assisted organ segmentation, a cloud research mode (where policy permits), adaptations for paediatric and rare-disease protocols, and health-economic modules to inform policy and budget decisions. These additions aim to deepen clinical utility while keeping the system deployable in both high- and low-resource settings.

Conclusion

Equira™ represents a breakthrough in nuclear medicine dosimetry. By making personalised dosimetry accessible and affordable, it can improve safety, efficacy, and consistency of radiopharmaceutical therapy across diverse care settings. Our broader aim is clear: to advance precision care for every patient, irrespective of geography or socioeconomic status.

Acknowledgements

We acknowledge the support of Taylor's University, the Malaysian Nuclear Agency, the Philippine Nuclear Research Institute, and the Japan Atomic Energy Agency (JAEA). The project is funded by the Prototype Research Grant Scheme (PRGS/1/2023/SKK01/TAYLOR/01/1) under the Ministry of Higher Education, Malaysia, and partially supported by the DOST-HRDP Scholarship Programme.

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Chapter 5

A Low-cost, Portable, and AI-powered Device for Cardiac Investigation

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Abstract

With cardiovascular diseases ranking as a significant cause of mortality worldwide, timely diagnosis and effective monitoring are essential. In recent decades, interest in non-invasive cardiovascular monitoring technologies has increased significantly, driving research toward the development of advanced tools that can enhance the diagnosis and clinical management of cardiac disorders. Electrocardiography (ECG) is the gold-standard technique for analysing the heart's electrical activity and is widely used to detect rhythm and conduction abnormalities. However, an ECG alone is not always sufficient to identify all pathologies. Disorders related to valvular function, such as heart murmurs, require an acoustic investigation. In this context, phonocardiography (PCG) is a valuable complementary tool, commonly referred to as an electronic stethoscope, that enables the recording and analysis of heart sounds produced during the cardiac cycle.

We have designed and manufactured a low-cost, modular prototype for the early detection and home monitoring of cardiac disorders (MotemaSens). This paper presents preliminary results, with clinical validation ongoing. The device is capable of simultaneously collecting heart sounds (similar to a digital stethoscope) and ECG (up to 12 leads), supported by AI for rapid data interpretation. Furthermore, the device collects the electromyogram (EMG) and has spare channels for additional sensors, such as temperature or pulse oximetry, and is ISO 13485 certified. Our AI algorithm won first prize in the PhysioNet Challenge 2022. The low cost and portability (6 x 6 cm) of MotemaSens make it suitable for both high- and low-income settings, addressing the lack of appropriate technical platforms in low- and middle-income countries (LMICs).

Keywords: *Multimodal and multifunctional, Low-cost device, LMICS, Electrocardiogram, Electromyogram*

Introduction

According to the World Health Organisation (WHO), cardiovascular diseases (CVDs) are the leading cause of death, with a mortality rate of 32% of all global deaths¹, making CVD a significant global public

¹WHO. "Cardiovascular Diseases (CVDs)." July 31, 2025. [https://www.who.int/news-room/fact-sheets/detail/cardiovascular-diseases-\(cvds\)](https://www.who.int/news-room/fact-sheets/detail/cardiovascular-diseases-(cvds))

health crisis. CVD is an umbrella term for all heart and blood vessel diseases. It commonly refers to coronary heart disease and stroke. However, other heart conditions can affect heart valves, muscles, or rhythm. Valvular heart disease (VHD) occurs when heart valves do not function correctly, resulting in either valvular stenosis (narrowing) or valvular insufficiency (leaking), which significantly contributes to the loss of physical function, quality of life, and longevity. Due to an ageing population, around 1.5 million people in the United Kingdom (UK) aged 65 or over are thought to have VHD, including aortic stenosis and mitral regurgitation. Estimates suggest that this will double by the year 2046 and rise to 3.3 million in 2056². Timely treatment is essential because the risk of dying from valve disease is proportional to the severity and symptoms of heart failure³. Timely treatment can be achieved by regular screening, monitoring and intervention. Low- and middle-income countries (LMICs) contribute a greater share to the global burden of CVDs, with these conditions being responsible for 80% of all cardiovascular deaths worldwide⁴. Whilst effective measures are being put in place in high-income countries, resulting in a decline in the rate of CVD, CVD mortality is on a steady rise in LMICs, with rates of up to 300–600 deaths attributed to CVD per 100,000 population and is projected to increase, causing preventable loss of lives⁵. The poor have the worst outcomes from non-communicable diseases, including CVD, mainly because of their inability to access or afford preventative services and ongoing treatments. This calls for a more integrated approach for the detection, prevention, and management of CVDs in LMICs.

The underdevelopment and technological under-equipment in this medical sector are primarily due to the fact that all equipment has been imported for a long time, resulting in exorbitant costs that are inaccessible to the majority of the population. To contribute to this approach, we have designed and manufactured a low-cost, modular, and multifunctional prototype for the early detection and home monitoring of CVDs (MotemaSens). The device is capable of simultaneously collecting heart sounds (similar to a digital stethoscope) and ECG (up to 12 leads), supported by AI for rapid data interpretation. Furthermore, the device can measure the electromyogram (EMG) and has multiple input channels ready for the addition of other sensors, such as temperature or pulse oximetry, and is ISO 13485 certified. The low cost and portability (6 x 6 cm) of the system make it suitable for both high- and low-income settings, addressing the lack of appropriate technical platforms in LMICs.

²Joanna L. D’Arcy et al., “Large-scale Community Echocardiographic Screening Reveals a Major Burden of Undiagnosed Valvular Heart Disease in Older People: The OxVALVE Population Cohort Study,” *European Heart Journal* 37, no. 47 (June 26, 2016): 3515–22, <https://doi.org/10.1093/eurheartj/ehw229>

³Rick A. Nishimura et al., “2014 AHA/ACC Guideline for the Management of Patients With Valvular Heart Disease: Executive Summary,” *Circulation* 129, no. 23 (March 4, 2014): 2440–92, <https://doi.org/10.1161/cir.0000000000000029>

⁴Gregory A Roth et al., “Global, Regional, and National Age-sex-specific Mortality for 282 Causes of Death in 195 Countries and Territories, 1980–2017: A Systematic Analysis for the Global Burden of Disease Study 2017,” *The Lancet* 392, no. 10159 (November 1, 2018): 1736–88, [https://doi.org/10.1016/s0140-6736\(18\)32203-7](https://doi.org/10.1016/s0140-6736(18)32203-7)

⁵World Health Organization. *Global Status Report on Noncommunicable Diseases 2010*. Geneva: World Health Organization, 2011.

This paper presents the results of verification tests, validation tests, and preliminary data collection of 12-lead ECG signals.

Methods

The device underwent bench tests for signal verification using known input signals across two channels to evaluate gain accuracy, frequency response, linearity, signal-to-noise ratio, and crosstalk. The device has also been validated against a commonly used gold-standard system (referred to as the reference device) for EMG acquisition from the bicep muscles at a moderate force level.

We collected pilot data on 12-lead ECG from six healthy individuals using gel electrodes and dry electrodes. Dry electrodes are reusable, thereby helping to address the challenges associated with the supply chains of disposable gel electrodes in rural areas.

Results and Discussion

Verification tests

The verification tests of the two channels of the device showed the following characteristics:

- Gain accuracy: The two channels displayed similar gain profiles across all voltage inputs (0.1-4.7 V) with a mean absolute difference of -56 ± 5.3 dB.
- Frequency response: The two channels consistently measured a 130 Hz input as 129.9 Hz across all amplitudes and exhibited a linear behaviour (input vs output) between 0 and 1000 Hz.
- Crosstalk: When connecting one channel at a time, minimal crosstalk was observed with correlation values between 0.009 and 0.3.

Validation tests

Figure 1 shows EMG traces recorded using our device and the gold-standard reference system, respectively. The baseline amplitudes were 1.4 μ V and 8.4 μ V for MotemaSens and the reference system, respectively. The frequency response obtained from our measurements also aligns with the range reported in the literature, which states that the optimum EMG frequency band lies between 50 and 150 Hz⁶.

12-lead ECG data

Figure 2 depicts an example of a 12-lead ECG recording using dry electrodes. The next step is to consult cardiologists to examine the wave morphologies for clinical purposes. We are also working on standardising the ECG results to be shared via WhatsApp or email. ECG traces collected using gel and dry electrodes exhibited similar shapes with correction coefficients ranging from 0.7 to 0.91 and 0.89 to 0.98 for derived and measured channels, respectively.

⁶Laxmi Shaw and Sangeeta Bhaga. "EMG Signal Analysis for Diagnosis of Neuromuscular Diseases by Using PCA and PNN." International Journal of Engineering Science and Technology 4, no. 10 (Oct 2012): 4453–59.

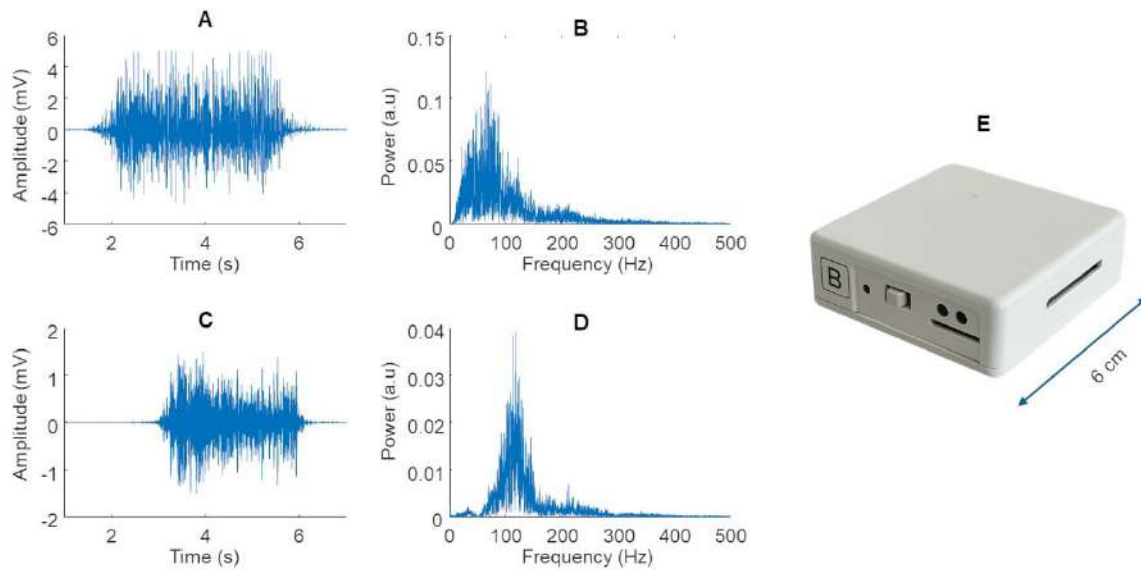


Figure 1: Example of A) EMG signal from the reference gold-standard device with B) associated power spectrum. C) EMG signal from the MotemaSens device with D) associated power spectrum; E) A photo of MotemaSens.

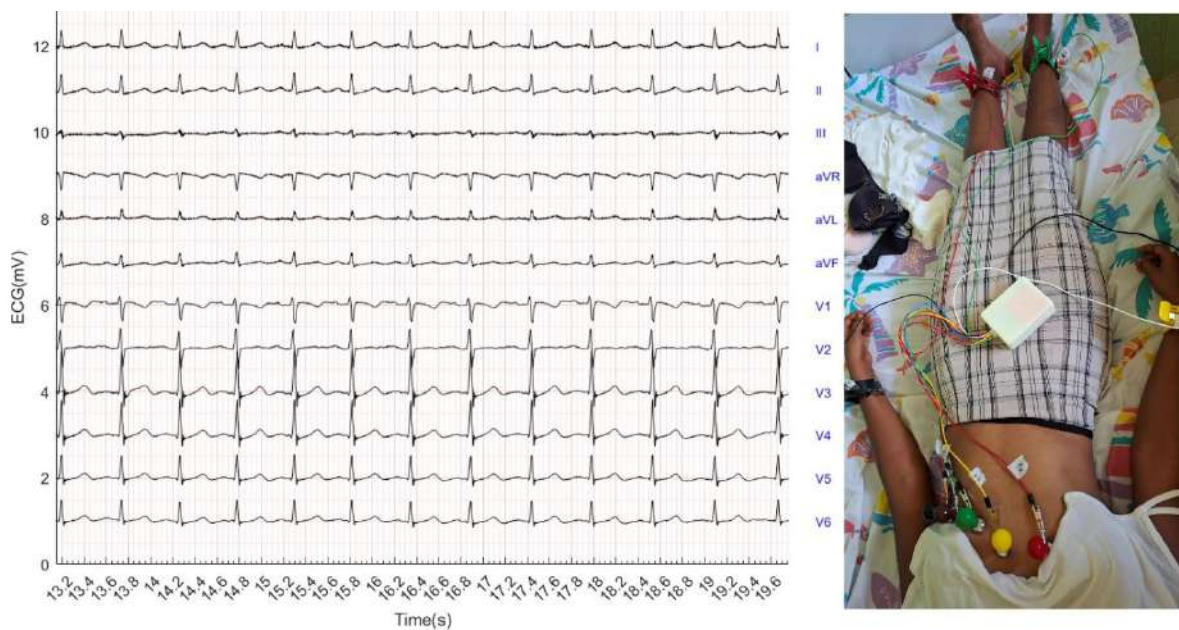


Figure 2: An example of a 12-Lead ECG recording of a female participant (23 years old) using reusable dry electrodes.

Heart sounds measurement

MotemaSens can measure heart sound (using an external electronic stethoscope) and ECG concurrently for improved diagnostics. The traces are superimposed in Figure 3 for visualisation purposes. In the user interface, they are shown on different subplots that are synchronised in time. In this example, the SNRs of heart sound and ECG are 16.8 dB and 27.9 dB, respectively. Our AI algorithm for classifying abnormal murmurs achieved a sensitivity of 90%, winning first prize in the PhysioNet Challenge 2022.

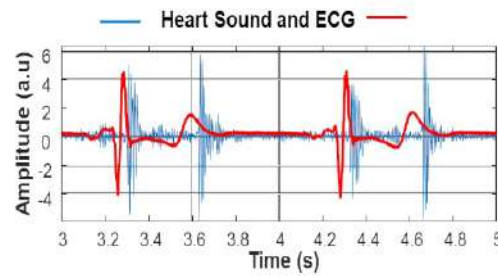


Figure 3: An example of concurrent recording of heart sounds and ECG superimposed for visualisation purposes.

Conclusion

This paper describes a low-cost, portable, and AI-powered device primarily designed for heart investigations, such as ECG and heart sounds. Furthermore, the input amplifier is also configured to accept other biomedical signals, such as EMG. In the future, we will also be able to collect other biosignals. Verification tests demonstrated the device's ability to produce consistent gain values across voltage levels, maintain frequency components without distortion, and achieve high signal-to-noise ratios. With the current tests being conducted in the DRC, we have strong evidence that such a device addresses the challenges associated with the lack of dedicated equipment in LMICs. The device is designed to be built and maintained in low-resource areas.

Acknowledgements

The development of this prototype was funded by the King's College London Medical Research Council Impact Accelerator Account.

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Shaw, Laxmi, and Sangeeta Bhaga. "EMG Signal Analysis for Diagnosis of Neuromuscular Diseases by Using PCA and PNN." *International Journal of Engineering Science and Technology* 4, no. 10 (Oct 2012): 4453–59.

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Chapter 6

Edge AI-enabled Smart Glasses and Companion Robots for In-home Health Monitoring and Medication Adherence

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Abstract

Elderly and chronic disease patients face significant challenges in reliably receiving essential medical assistance and maintaining medication adherence at home, especially when not hospitalized. This paper presents an overview of novel technologies for personal health monitoring and medication adherence in home environments, combining innovative smart glasses with companion autonomous robotic systems. The pioneering aspects include the use of novel low-power radar sensing, ultra-wideband (UWB) positioning, hybrid electrooculography (EOG) eye-tracking, and Edge AI technologies, enabling accurate patient health monitoring, enhanced human-machine interaction (HMI), and intelligent robotic platforms that can make autonomous decisions using embedded reasoning. This improves privacy, response latency, and independence from internet connectivity. On the wearable side, through the fusion of low-power radars and efficient EOG-based eye tracking, it is possible to continuously track vital signs and gaze-based interactions, facilitating timely interventions and advanced HMI. These smart glasses detect early signs of health deterioration, potentially preventing severe health complications. Combining on-body monitoring with robotic assistance proactively reduces health risks. Edge AI-powered robots are proposed to support medication adherence and dietary management, addressing medication errors that currently affect nearly half of chronic illness patients receiving home care. Ultimately, the proposed approach delivers tangible improvements in health outcomes, quality of life, and societal well-being.

Keywords: *Smart Glasses, Radar Sensing, Eye Tracking, Human-Machine Interaction, Assistive Robotics*

Introduction

Global healthcare systems are under unprecedented strain due to demographic shifts, aging populations, and the prevalence of chronic diseases. Elderly individuals and patients with conditions such as cardiovascular disease, diabetes, and respiratory illnesses often require continuous monitoring and timely interventions. Yet, conventional solutions, hospital-based monitoring or consumer-grade wearable, are either too resource-intensive or insufficiently reliable for everyday living^{1,2}.

¹Minjae Choi et al., “Living Longer but in Poor Health: Healthcare System Responses to Ageing Populations in Industrialised Countries Based on the Findings From the Global Burden of Disease Study 2019,” *BMC Public Health* 24, no. 576 (February 22, 2024), <https://doi.org/10.1186/s12889-024-18049-0>

²World Health Organization: WHO. “Ageing and Health.” October 1, 2025. <https://www.who.int/news-room/fact-sheets/detail/ageing-and-health>

This paper presents three key technological trends and pioneering technologies designed to address these challenges:

- Contactless radar-based vital sign monitoring: Recent advances in millimetre-wave radar allows the integration of non-contact heart rate and respiration sensing into smart glasses, providing unobtrusive and motion-resilient monitoring.
- Hybrid electrooculography (EOG) eye-tracking for natural interfaces: The ElectraSight system demonstrated a fully onboard, low-power, hybrid contact/non-contact EOG solution for smart glasses, achieving accurate gaze tracking at just 8.85 mW, with continuous operation beyond 3 days. This transforms glasses into intuitive human-machine interactions (HMIs), bridging user intention and digital/robotic systems.
- Semi-autonomous assistive robots: Quadruped robots, guided by gaze-based interaction, extend human capability in daily tasks, from fetching objects to medication delivery, with an average positioning error below 20 cm.

By combining these technologies, a unified framework can be envisioned: smart glasses serve as the hub, simultaneously sensing vital signs, tracking gaze, and acting as the interface to robotic companions. This dual role creates a human-centred assistive ecosystem that supports independence, improves healthcare outcomes, and preserves privacy by processing data locally through Edge AI.

Results

The system concept comprises of three elements illustrated in separate subsections.

Hybrid eye tracking with ElectraSight

ElectraSight introduces a hybrid eye-tracking solution based on EOG. By combining contact electrodes for high signal fidelity and capacitive electrodes for improved comfort, the system captures gaze data continuously. All processing is performed onboard a GreenWaves GAP9 RISC-V processor, using convolutional neural networks and temporal models optimised for embedded execution.

Testing confirmed a classification accuracy of 92% for basic gaze classes and 84% for extended classes, with a latency under 60 milliseconds and a sensing-to-decision pipeline contribution below 1 millisecond. The power consumption of 8.85 mW supports more than 3 days of continuous operation without recharging³.

Radar-embedded smart glasses for autonomous vital sign monitoring

A pioneering approach to vital sign monitoring is the integration of radar sensors directly into the same form factor as smart glasses. These radar-enabled glasses perform autonomous, continuous vital sign monitoring without requiring skin contact. The proposed system incorporates a 60 GHz frequency-

³Schärer et al. “ElectraSight: Smart Glasses with Fully Onboard Non-Invasive Eye Tracking Using Hybrid Contact and Contactless EOG.”

modulated continuous-wave (FMCW) radar (Infineon BGT60UTR13DAiP) together with a low-power microcontroller, enabling real-time, fully onboard signal processing. By detecting subtle arterial micro-motions, the radar eliminates the limitations of optical or electrode-based methods. The signal processing pipeline comprises chirp accumulation, fast Fourier transform (FFT), displacement estimation, and frequency analysis, achieving full execution in only 1.9 milliseconds. This design demonstrates that reliable and unobtrusive monitoring can be realised within the compact, socially acceptable form factor of smart glasses. Quantitative evaluation with three subjects showed mean errors of 5.20, 4.07, and 3.64 beats per minute compared to a Polar H10 chest strap reference. The device consumed only 29.7 mW, allowing more than 20 hours of continuous operation on a 175 mAh battery⁴.

Gaze-guided semi-autonomous quadruped robots

The third component of this framework is the use of gaze to control assistive robots. A Unitree Go1 quadruped robot was equipped with LiDAR, RGB-D cameras, and an Intel NUC for onboard processing. Gaze data from Pupil Labs Neon glasses were transformed into the robot's perception frame using image matching. The Robot Operating System navigation stack was employed for obstacle avoidance and dynamic path planning. Experiments confirmed that the robot could reach gaze-indicated targets with an average positioning error of 19.7 cm (± 8.1 cm). When using the SURF image-matching algorithm, the system achieved 0.215 second processing latency with average power consumption of around 52 W, outperforming neural-based alternatives under CPU-only conditions. Navigation was reliable even in cluttered environments, and latency remained suitable for real-time interaction⁵.

Results and Discussion

The results across these three systems demonstrate both feasibility and synergy. Radar-enabled smart glasses provided accurate, motion-resilient heart rate monitoring at less than 30 mW, supporting more than 20 hours of continuous operation. ElectraSight confirmed that eye tracking can be achieved entirely onboard, with accuracy above 90% and energy efficiency sufficient for 3 days of continuous use. The gaze-guided robot successfully navigated complex indoor environments, reaching targets within 20 cm on average and responding in under a quarter of a second. Together, these contributions create a new paradigm in assistive healthcare. The smart glasses act as both sensors and interfaces, continuously monitoring vital signs while simultaneously interpreting gaze commands. The robot serves as the physical actuator, executing tasks that extend the user's autonomy. For example, if radar-based monitoring detects an abnormal heart rate, the system could automatically dispatch the robot to retrieve medication or alert caregivers. Conversely, when the user requires assistance, they can direct the robot simply by looking at an object or location. The combination of continuous monitoring, natural

⁴Joseph et al. "Non-invasive Contactless Heart Rate Monitoring Onboard Ultra-low Power Smart-glasses." *IEEE Sensors*, October 19, 2025, 1–4.

⁵Paul Joseph et al., "Gaze-Guided Semi-Autonomous Quadruped Robot for Enhanced Assisted Living," *IEEE Sensors Applications Symposium (SAS)*, July 23, 2024, 1–6, <https://doi.org/10.1109/sas60918.2024.10636523>

interaction, and robotic support addresses key healthcare challenges, including medication adherence, fall prevention, and real-time emergency response. It also supports ethical principles of privacy, since all data are processed locally on embedded devices rather than transmitted to the cloud.

Conclusion

This paper presented a vision for integrating radar-based health monitoring, hybrid EOG eye tracking, and gaze-guided robotic assistance into a unified framework for assisted living and home healthcare. Radar-enabled glasses demonstrated real-time, low-power, and accurate heart rate monitoring. ElectraSight provided onboard gaze tracking at high accuracy and minimal power consumption, enabling intuitive interaction. The gaze-guided quadruped robot validated the feasibility of natural and semi-autonomous human-robot interaction in cluttered environments. Taken together, these innovations illustrate how smart glasses can serve as both a health monitor and a control interface, while robots act as mobile companions that provide physical support and ensure safety. This synergy directly addresses healthcare challenges related to aging populations and chronic disease management. Future research will extend biometric sensing, enhance robotic manipulation, and evaluate systems in real-world clinical environments. Ultimately, the combination of wearable sensing, intuitive gaze-based interaction, and robotic autonomy has the potential to transform healthcare delivery and improve independence, quality of life, and safety for millions of patients worldwide.

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Chapter 7

Transforming Preeclampsia Care Through Cross-disciplinary Innovation: From Platelet Biomarkers to Real-time Clinical Decision Support

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Abstract

Preeclampsia remains a leading global cause of maternal and infant morbidity and mortality, with rising incidence and a strong association with increased lifelong cardiovascular risk in women. Despite its burden, current screening methods in early pregnancy identify only a small fraction of cases, while diagnosis after symptom onset (post-20 weeks gestation) often comes too late, relying on clinical and biochemical tests with limited sensitivity and specificity. These delays contribute to preventable complications and missed opportunities for early intervention. To address this critical clinical gap, our team has developed a fully integrated, whole-pregnancy solution for the early prediction and management of preeclampsia. Building on over 2 decades of foundational research into platelet biology and extracellular vesicles, we have identified novel, patent-pending platelet-derived biomarkers from maternal blood. These biomarkers underpin a diagnostic and prognostic test for use after 20 weeks, providing rapid, real-time clinical decision support in suspected preeclampsia cases via our AI-enabled platform. This translational programme exemplifies cross-disciplinary innovation, bringing together clinicians, scientists, engineers, and AI researchers across academic and hospital systems. By bridging discovery science with digital health, our approach aims to transform maternal care, reduce avoidable deaths, and improve long-term health outcomes for women and their families worldwide.

Keywords: *Preeclampsia, AI, Biomarkers, Platelets, Maternal Health*

Introduction

Preeclampsia toxemia (PET) is a serious, life-threatening hypertensive disorder of pregnancy, affecting approximately 1 in 12 pregnancies globally. It stands as a leading cause of maternal and perinatal morbidity and mortality, contributing to over 76,000 maternal deaths and 500,000 fetal and neonatal deaths annually¹. This complex multisystem disorder is characterised by the new onset or progression of hypertension after 20 weeks of gestation, accompanied by significant proteinuria or other organ dysfunction². The diagnosis and management of PET present significant challenges for clinicians due

¹Eric Ap Steegers et al., "Pre-eclampsia," *The Lancet* 376, no. 9741 (2010): 631–44, [https://doi.org/10.1016/s0140-6736\(10\)60279-6](https://doi.org/10.1016/s0140-6736(10)60279-6)

²Liona C. Poon et al., "Hypertensive Disorders of Pregnancy and Long-term Cardiovascular Health: FIGO Best Practice Advice," *International Journal of Gynecology & Obstetrics* 160, no. S1 (January 1, 2023): 22–34, <https://doi.org/10.1002/ijgo.14540>

to its diverse spectrum of clinical manifestations, with varying clinical course, onset, and symptoms among patients. The only definitive treatment for PET is the delivery of the fetus and placenta, regardless of gestational age. This often necessitates preterm birth, requiring clinicians to balance maternal safety against the substantial risks associated with early delivery³. Such decisions lead to over 5 million premature infant deliveries annually due to suspected or confirmed PET, with profound implications for neonatal health, long-term neurodevelopment, such as cerebral palsy, and global healthcare resources^{4,5}. Current clinical diagnosis relies on measuring blood pressure and proteinuria, which can be challenging, cumbersome, and uncertain. Symptoms poorly predict adverse outcomes, risking missed diagnoses. Moreover, once diagnosed, there is no reliable indicator of likely progression of the disorder, and no tool to support frontline staff in making the critical decision on the optimal timing for delivery, especially given the potential for rapid escalation. This clinical complexity demonstrates the urgent, unmet need for innovative, non-invasive, and personalised risk-based triage tools, which would facilitate early intervention before severe complications occur.

AI-powered Research: Bridging Platelet Biology and AI to Tackle Preeclampsia

Addressing this major global health challenge, professor Patricia Maguire and the interdisciplinary team at University College Dublin (UCD) and collaborators at the Royal College of Surgeons (RCSI) in Ireland have developed AI_PREMie, a groundbreaking, AI-powered clinical decision support tool designed to transform the diagnosis and management of PET. Rooted in decades of pioneering research in platelet biology and biomedical data science, AI_PREMie integrates cutting-edge machine learning (ML), biomarker discovery, and clinical medicine to deliver real-time, personalised risk assessments.

The foundational science of AI_PREMie emerged from the team's platelet-based biomarker discovery platform, PALADIN™ (PlAteLet bAsed DIagNostics), which captures the bioactive contents of the platelet releasate⁶⁻⁹. Utilising mass spectrometry-based proteomics on maternal blood samples, a distinct panel of biomarkers associated with PET was identified, including proteins involved in

³Khalid S Khan et al., "WHO Analysis of Causes of Maternal Death: A Systematic Review," *The Lancet* 367, no. 9516 (March 30, 2006): 1066–74, [https://doi.org/10.1016/s0140-6736\(06\)68397-9](https://doi.org/10.1016/s0140-6736(06)68397-9)

⁴Labib Ghulmiyyah and Baha Sibai, "Maternal Mortality From Preeclampsia/Eclampsia," *Seminars in Perinatology* 36, no. 1 (January 29, 2012): 56–59, <https://doi.org/10.1053/j.semperi.2011.09.011>

⁵Anouk Bokslag et al., "Preeclampsia: Short and Long-term Consequences for Mother and Neonate," *Early Human Development* 102 (September 20, 2016): 47–50, <https://doi.org/10.1016/j.earlhumdev.2016.09.007>

⁶J. Coppinger and P. Maguire, "Insights Into the Platelet Releasate," *Current Pharmaceutical Design* 13, no. 26 (August 28, 2007): 2640–46, <https://doi.org/10.2174/138161207781662885>

⁷Martin E. M. Parsons et al., "Platelet Releasate Proteome Profiling Reveals a Core Set of Proteins With Low Variance Between Healthy Adults," *PROTEOMICS* 18, no. 15 (June 22, 2018): e1800219, <https://doi.org/10.1002/pmic.201800219>

⁸Judith A. Coppinger et al., "Characterization of the Proteins Released from Activated Platelets Leads to Localization of Novel Platelet Proteins in Human Atherosclerotic Lesions," *Blood* 103, no. 6 (2004): 2096–2104, <https://doi.org/10.1182/blood-2003-08-2804>

⁹Sarah Kelliher et al., "Pathophysiology of the Venous Thromboembolism Risk in Preeclampsia," *Hämostaseologie* 40, no. 05 (May 25, 2020): 594–604, <https://doi.org/10.1055/a-1162-3905>

angiogenesis, endothelial dysfunction, and inflammation¹⁰. These biomarkers were validated across independent cohorts, demonstrating their ability to distinguish PET from healthy pregnancies, and even differentiate severe cases from milder forms of the disorder. Specifically, four carefully selected platelet-derived biomarkers, chosen for their shared diagnostic and prognostic capabilities in PET, now form the patent-pending biomarker panel of AI_PREMie. These are quantified using an immunological-based ELISA approach.

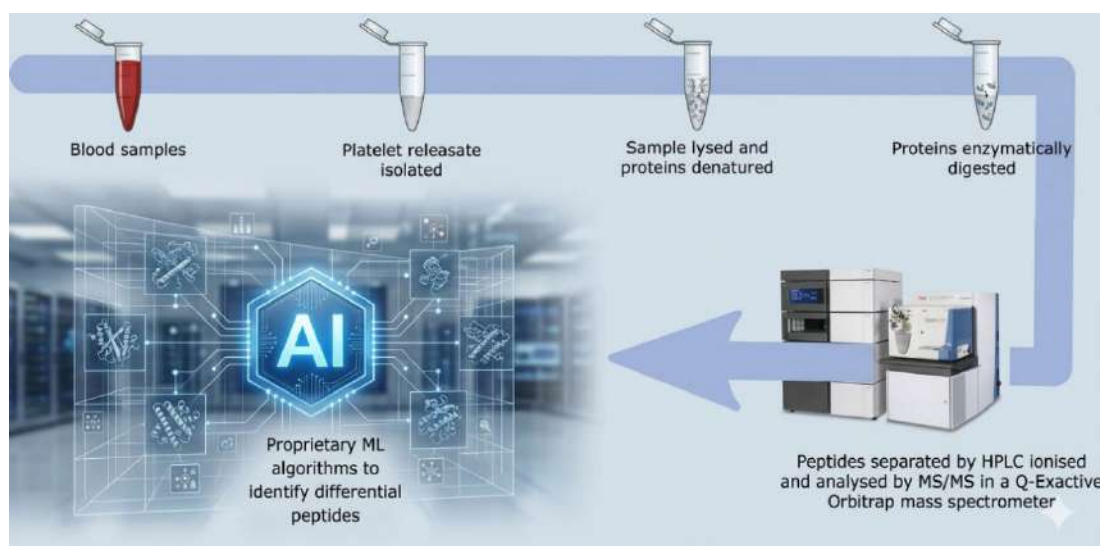


Figure 1: PALADIN: An integrative proteomic and machine learning workflow for the identification of diagnostic platelet-derived peptide signatures.

Blood samples are collected and processed to isolate the platelet releasate, representing the bioactive content released upon platelet activation. Isolated samples are lysed and proteins denatured, followed by enzymatic digestion to generate digested peptides. Peptides are then separated by high-performance liquid chromatography (HPLC), ionised, and analysed by tandem mass spectrometry (MS/MS) using a Q-Exactive Orbitrap mass spectrometer for high-resolution peptide identification and quantification. Quantitative proteomic data can be subsequently processed using ML algorithms to identify differentially expressed peptides associated with distinct diagnostic groups. This integrative approach enables the discovery of diagnostic peptide signatures and provides mechanistic insights into underlying disease aetiology.

Recognising the complex and multifactorial nature of PET and the limitations of predicting the condition accurately using biomarkers alone, the team harnessed artificial intelligence (AI) to integrate these biological signatures with a comprehensive set of clinical and demographic data. This rich dataset includes variables such as maternal age, Body Mass Index (BMI), blood pressure trends, and routine laboratory values. Using this rich dataset, a suite of ML models, including XGBoost, Random Forests, and Neural Networks, were trained to support clinicians at three key decision points: diagnosis, severity at diagnosis, and prediction of severity at delivery. The models demonstrated robust performance across all major tasks, achieving AUC values above 0.87, where AUC (area under the receiver operating

¹⁰Paulina B. Szklanna et al., “The Platelet Releasate Is Altered in Human Pregnancy,” *PROTEOMICS - CLINICAL APPLICATIONS* 13, no. 3 (October 15, 2018): e1800162, <https://doi.org/10.1002/prca.201800162>

characteristic curve) measures the model's ability to distinguish between positive and negative cases. By providing timely, evidence-based risk assessments, AI_PREMie empowers clinicians with actionable insights at critical decision points, while ensuring that all final clinical judgments and interventions remain fully under the clinician's authority.

Clinical Translation and Health System Impact

The development of AI_PREMie highlights the power of intersectoral collaboration, emerging at the intersection of biomedical innovation, clinical need, and advanced analytics. Crucially, its outputs have been co-designed with senior frontline clinicians to enable seamless integration into real-time obstetric triage and high-risk maternity care. From its inception, development has been shaped through close collaboration with clinical teams at the National Maternity Hospital, the Coombe Hospital, and the Rotunda Hospital.

The platform delivers actionable, evidence-based decision support precisely where and when it is needed. It generates personalised risk scores and visualisations, enabling clinicians to optimise care plans and make informed decisions on timing of delivery and clinical care. By identifying mothers with PET who are unlikely to progress to severe disease, unnecessary preterm or emergency deliveries, and their associated complications, can be avoided, improving outcomes for both mothers and infants. Health-economic modelling in Ireland indicates that widespread implementation of AI_PREMie could yield substantial cost savings while enhancing long-term maternal and neonatal health outcomes, providing a compelling case for integration into global maternity care pathways.

While end-to-end integration into clinical workflows is still under development, AI_PREMie will follow a clear pathway. When PET is suspected, clinicians order routine blood tests, from which the same sample is also taken for the AI_PREMie test. Our novel biomarkers are analysed on standard hospital equipment, where these results, combined with clinical variables and electronic health record (EHR) data, are analysed by AI_PREMie's proprietary algorithms to generate a clinician-friendly risk score. Seamless integration with major EHR platforms (e.g., *Epic*, *Cerner*) ensures that actionable decision support is delivered directly at the point of care to enable clinical decision making.

Conclusion

By transforming the diagnosis and management of preeclampsia, AI_PREMie is redefining how clinicians approach one of the leading causes of preventable maternal and neonatal mortality. Its integration of biomarkers, advanced AI, and clinical data enables earlier identification, more accurate risk stratification, and timely intervention where it matters most. With strong validation, strategic partnerships, and planned multicentre clinical studies, AI_PREMie is positioned to move from pioneering research to routine clinical practice, delivering true bench-to-bedside innovation. Beyond improving outcomes, it has the potential to reduce health inequities by making cutting-edge decision support accessible at the point of care in hospitals worldwide. At its core, AI_PREMie is on a mission to ensure that no woman dies while giving life, bringing intelligence to the bedside, empowering clinicians, and ultimately saving the lives of both mothers and babies.

Acknowledgements

The AI_PREMie project is supported by expert clinicians in Dublin's maternity hospitals: Prof Mary F. Higgins (UCD Perinatal Research Centre, National Maternity Hospital), Prof Jennifer Donnelly (RCSI School of Medicine, Rotunda Hospital), Prof Amy O'Higgins (UCD Centre for Human Reproduction, Coombe Women and Infants University Hospital), and Prof Fionnuala Ní Áinle (Department of Haematology, Mater University Hospital and Rotunda Hospital; School of Medicine, University College Dublin). The AI_PREMie project is currently funded by Enterprise Ireland's (EI) Commercialisation Fund, with earlier support from Science Foundation Ireland (SFI) and the Health Research Board (HRB). We gratefully acknowledge our collaboration with the SAS Institute, whose software and expertise have been instrumental in the development of the machine-learning algorithms.

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Chapter 8

MONA: A Robotic Patient Simulator for Occupational Therapists Training

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Abstract

Most developed countries are facing the challenge of ageing populations and the associated care demands. Robotics and artificial intelligence (AI) can provide support for healthcare professionals. In this study, we present MONA, a robotic manikin for training Occupational Therapists (OTs) in patient assessment scenarios. The manikin incorporates over 4000 tactile sensing points to capture pressure distribution and magnitude during interactions. Silicone layers provide skin-like texture, and a motorised knee simulates mobility impairments. Sensor data are processed real-time to trigger adaptive responses, including vocal reactions and leg movements when pain thresholds are exceeded. Trainers can configure patient profiles, monitor sessions through a graphical user interface (GUI) and record data for later analysis.

The system was successfully deployed in a preliminary evaluation session with OT professionals, where it provided realistic and varied patient scenarios. Data from these interactions were captured in a questionnaire that will inform the development of hardware features and AI-driven patient models to further enhance training realism and adaptability.

Keywords: *Robot Patient Simulator, Tactile Sensing, Medical Training, Occupational Therapy*

Introduction

Robotics and artificial intelligence (AI) promise to revolutionise the healthcare sector¹ and together might provide a solution to one of the great challenges facing developed nations: population ageing. In the United Kingdom (UK), 18% of people are aged 65 or over² and globally this group is expected to double to 1.6 billion by 2050³. Meeting their care needs will require significant efforts and innovations to support care professionals and reduce the strain on the workforce.

¹Pierre E. Dupont et al., “A Decade Retrospective of Medical Robotics Research From 2010 to 2020,” *Science Robotics* 6, no. 60 (November 10, 2021), <https://doi.org/10.1126/scirobotics.abi8017>

²UK Parliament. “The UK’s Changing Population.” House of Commons Library, July 16, 2024. Accessed September 6, 2025. <https://commonslibrary.parliament.uk/the-uks-changing-population/>

³United Nations, Department of Economic and Social Affairs, Population Division. *World Population Prospects 2022: Summary of Results*, 2022.

During training, students are given very limited opportunities to experience with real patients⁴, and robotic patient simulators can provide a worthy alternative⁵. Existing systems, though, usually only recreate just one limb, or half of the body and lack cognitive behaviour⁶. Some full-body high-fidelity patient simulators (HFPS) are available, but have limited sensors and actuators, focusing on breathing and hearth-related conditions. Crucially, large-area tactile sensing is still missing. Medical diagnosis or physiotherapy frequently requires interaction through touch⁷. Capturing and processing such information onboard the HFPS is therefore essential for it to simulate realistic reactions, such as pain after a forceful interaction, or a relaxed state after a calming stroke.

We present MONA, the first full-body robotic patient simulator with integrated tactile sensing for AI-driven reactive control (Figure 1). The robot was developed in collaboration with Occupational Therapists (OTs) to decide sensor morphology and placement for two assessment scenarios: lower-leg range of motion and seating posture assessments. The robot was presented to 13 OTs, and their feedback was captured in a questionnaire that confirmed its satisfactory performance for preliminary deployment with OT students.

Materials and Methods

The robot design

Built from a modified nursing manikin, MONA has an RMD-X8-P9-25-C-N motor (MyActuator, China) integrated into the left knee. This unit provides high torque, backdrivability, and can fit within the knee profile. The manikin's left thigh and full lower leg were replaced with skin-coloured Polylactic Acid (PLA) substitutes, 3D printed on a Carbon X1 printer (BambuLab, China). Cables run internally for a clean, natural appearance.

⁴Angelo Dante et al., "From High-Fidelity Patient Simulators to Robotics and Artificial Intelligence: A Discussion Paper on New Challenges to Enhance Learning in Nursing Education," in *Advances in Intelligent Systems and Computing*, 2020, 111–18, https://doi.org/10.1007/978-3-030-52287-2_11; Shun Ishikawa et al., "Assessment of Robotic Patient Simulators for Training in Manual Physical Therapy Examination Techniques," *PLoS ONE* 10, no. 4 (April 29, 2015): e0126392, <https://doi.org/10.1371/journal.pone.0126392>

⁵Zhifeng Huang et al., "Robot Patient Design to Simulate Various Patients for Transfer Training," *IEEE/ASME Transactions on Mechatronics* 22, no. 5 (July 25, 2017): 2079–90, <https://doi.org/10.1109/tmech.2017.2730848>; Nancy Robert, "How Artificial Intelligence Is Changing Nursing," *Nursing Management* 50, no. 9 (August 17, 2019): 30–39, <https://doi.org/10.1097/01.numa.0000578988.56622.21>; S. Abe et al., "Educational Effects Using a Robot Patient Simulation System for Development of Clinical Attitude," *European Journal of Dental Education* 22, no. 3 (November 1, 2017): e327–36, <https://doi.org/10.1111/eje.12298>

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⁶Dante et al., "From High-Fidelity Patient Simulators," 111–18.

⁷Raffaele Andrea Buono, Minna Nygren, and Nadia Bianchi-Berthouze, "Touch, Communication and Affect: A Systematic Review on the Use of Touch in Healthcare Professions," *Systematic Reviews* 14, no. 42 (2025), <https://doi.org/10.1186/s13643-025-02769-4>; Liang He et al., "Robotic Simulators for Tissue Examination Training With Multimodal Sensory Feedback," *IEEE Reviews in Biomedical Engineering* 16 (April 19, 2022): 514–29, <https://doi.org/10.1109/rbme.2022.3168422>

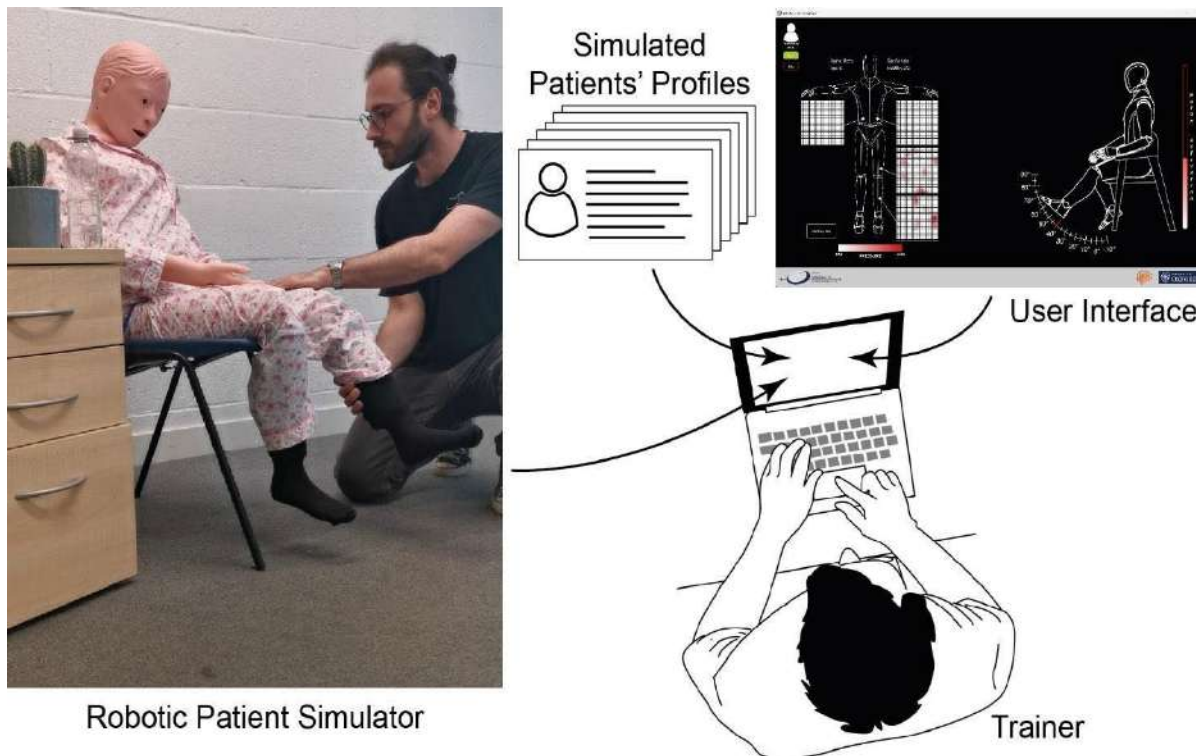


Figure 1: The robotic patient simulator for occupational therapists training and its intended use case.

Four FSR sheets (15 cm × 15 cm) record OT-robot interactions through custom-designed USB-powered readouts (ESP32S3, ADG731, AD4000, and SN74HCS595) for fast sampling of the 256 sensors per sheet. After discussions with OTs and having observed them perform the target assessments on the manikin, sensors were placed around the left lower leg, over the left thigh, and over the left and right ilium bones, symmetric about the manikin's sagittal plane. Additionally, 3.5 mm-thick silicone layers (DragonSkin 00-10, SmoothOn, US) cover the leg sensors for skin-like feel; in the pelvis, an additional layer of softer Ecoflex 00-30 silicone replicate fatty tissues. A flexible PCB with 16 RGBW LEDs is placed under the lower-leg silicone layer to simulate conditions like bruising or oedema. Finally, a loudspeaker enables pain vocalisation.

The user interface

The Python-based program consists of two threads. One acquires sensors and motor data for logging, the other processes the data for visualisation and to feedback information to the manikin. The interface displays one heatmap for each FSR sheet, while a protractor and a linear gauge show the knee angle and motor output torque respectively.

At launch, the trainer selects a patient profile defining age, sex, mobility, pain thresholds for sensor regions, and individual LED colours. When pressure on a skin area exceeds its threshold, the loudspeaker plays pre-recorded sounds, varying by sex and pain intensity. Motor torque is programmed as a linear function of knee angle, with slope and maximum set by the mobility range (1–3) in the patient profile. Behaviour was tuned with feedback from OTs to model mobility from normal to arthritic knees. If lower-leg pain thresholds are crossed, the motor triggers a sudden backward jerk, simulating spasm and muscle tension.

The questionnaire

The questionnaire consisted of three parts: (1) demographic of the participants, previous touch-related training experiences, and general perceptions about robots, (2) participants' feedback after simulating a passive range of movement assessment on the lower leg, and (3) longer reflection after the interaction with MONA. All questions related to the manikin were to be answered on a scale from 1 (not at all) to 5 (very much).

A total of 13 OTs (10.6 years of experience on average, $SD=11.14$) completed the questionnaire (c. 20 mins), with six interacting with the robot in full (c. 10 mins). The interaction was supervised by the platform developers for health and safety. Other participants could observe the interactions whilst filling the questionnaire.

Results and Discussion

An overwhelming 77% of OTs highlighted a strong need for systems like MONA during training (Figure 2), with the remaining 23% finding it somewhat useful. Additionally, 54% reported very little to no training in touch and its functional or affective use, and only 7% gave a top rating, though all strongly agreed that touch training is important for OT students.

Regarding robot interaction, 50% found MONA somewhat to very useful in its current form, while 83% believed an improved version would be an important tool. MONA's responses to painful stimuli, physically and verbally, were appreciated, though 66% reported pain thresholds were too low. A future ability to understand vocal prompts was desired by 66%, and 83% found LED visual cues for sore spots very acceptable.

Key improvements relate to appearance and realism (joint degrees of freedom, leg weight), although 50% felt the knee motor resistance adequately represents low mobility, supporting the current motor choice. Half of participants found the interface intuitive, with 33% rating it very intuitive. All agreed MONA is an important training tool for OT students.

Conclusion

In summary, MONA addresses key needs of OT trainees by enabling early and frequent practice with patients in a controlled setting. Standardised, repeatable scenarios, and recorded interactions provide insights into how clinical professionals use touch, both for assessment and non-verbal communication. This allows comparisons between trainees and experienced OTs and the creation of datasets for more realistic patient profiles, a focus area following OT feedback.

Having validated the current version, we are already working on an AI pipeline (speech-to-text, LLM, text-to-speech) to understand and respond to trainee prompts. Interaction datasets will support gesture recognition algorithms, improving robot responses to tactile cues. Future improvements will feature a more articulated manikin for enhanced realism. We hope MONA will serve as a first-of-its-kind device to open new avenues of medical AI-empowered training, for better healthcare and a more sustainable future.

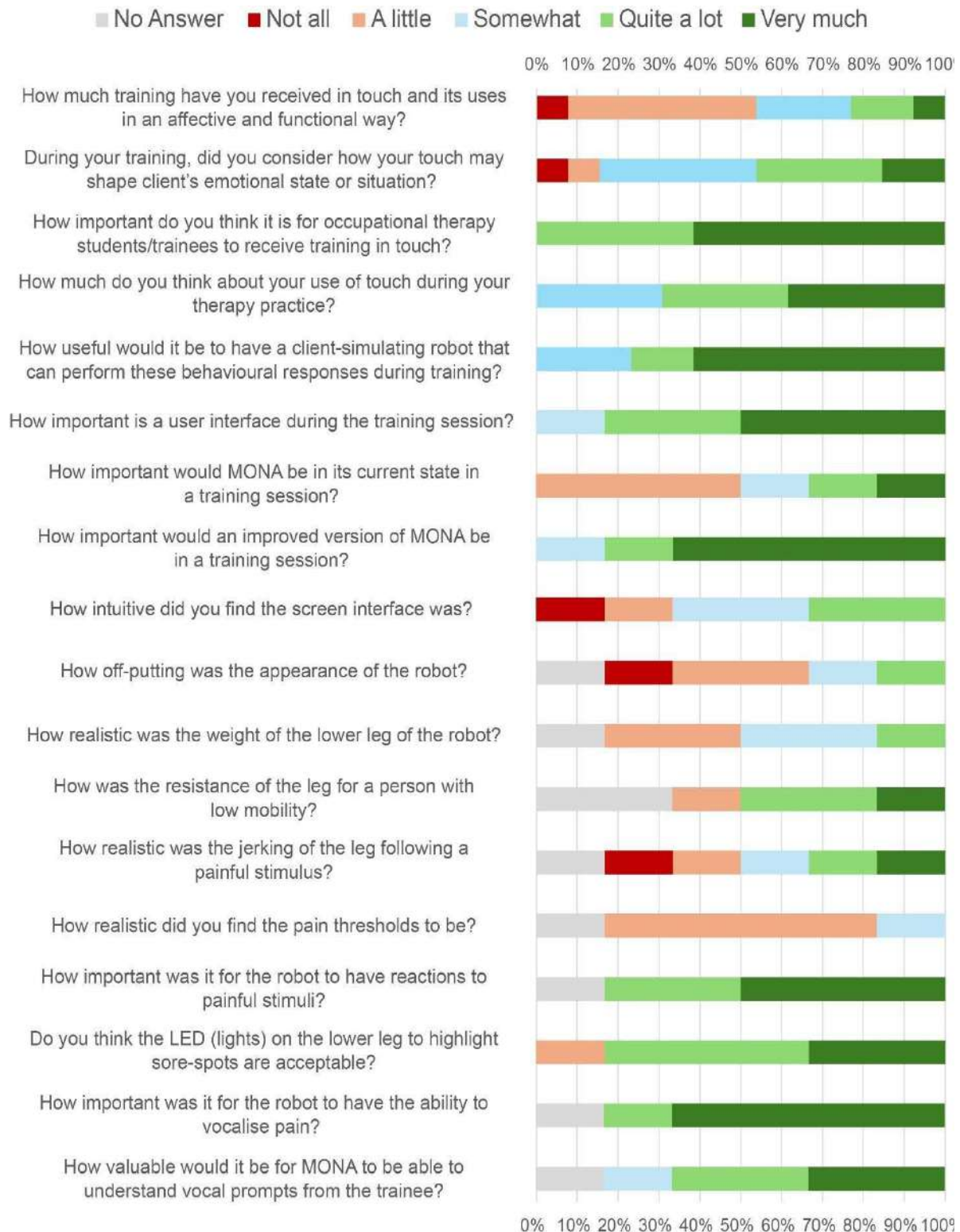


Figure 2: Summary of the questionnaire results of the preliminary deployment with 13 OTs.

Acknowledgements

We acknowledge the support of the EPSRC, who funded the project through the Programme Grant “From Sensing to Collaboration” and of the Oxfordshire County Council for hosting us during the preliminary deployment during the 2024 Occupational Therapy Week.

Ethical Approval

Ethical approval was acquired via UCL UCLIC Research Ethics Committee [UCLIC_2022_001_Berthouze].

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Chapter 9

PCAD: Prosthetic Comfort by Design–An Educational Innovation in Prosthetic Measurement

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Abstract

Over 40 million people with lower-limb amputation have to overcome significant challenges to acquire and use a prosthetic device. For patients seeking to regain mobility, the most important aspect in rehabilitation is the fit and comfort of a simple low-cost connecting socket. But, with each socket currently crafted entirely by hand, the existing trial-and-error fitting approach can take many hours of clinical time, and multiple visits. With ongoing resource and skill shortages, the biggest issue now facing providers and payers of prosthetic care is the time it takes for a prosthesis to be designed, produced, and delivered. Healthcare systems seek cost-effective solutions that drive productivity and improve outcomes. By modernising prosthetic care provision through advanced digital fitting and fulfilment technologies, prosthetic comfort by design (PCAD) can enhance patient accessibility to significantly improve the quality of life for millions of prosthetic users worldwide.

Based on extensive patient-centric research conducted at the United Kingdom's (UK) leading prosthetic teaching centre, PCADs have developed a transformative, digital limb-scanning solution that dramatically improves the productivity of socket fitting process. What used to take hours, now takes seconds. Our proprietary solution produces an accurate 3D representation of a limb under "loaded" conditions to provide a more reliable socket fit, reduced tissue pressure, and improved long-term patient comfort. The image is then converted into a digitised software measurement model with which to rapidly deliver an ultra-comfortable, uniquely fitted socket produced using modern fabrication techniques. Data produced also provide a unique patient record that can then be used to monitor limb health, track physical changes over time, or submitted as evidence for reimbursement purposes with healthcare payers. Integrating seamlessly into today's modern clinics, PCAD's process is data driven, consistent, and automated; such that socket fitting is no longer limited by the availability, skill, and experience of individual human prosthetist's to improve the productivity of prosthetic care provision.

Keywords: *Prosthetics, Shape-capture, Socket, CAD, CAM*

Introduction

Worldwide incidence of amputation in the developed world is estimated to be around 1.5/10,000. Numbers are rising due to increased life expectancy and the rise in non-communicable diseases such as diabetes (forecast to reach 522 million by 2030)¹. The diabetic population has an increased risk of lower

¹J. Aaron Barnes et al., "Epidemiology and Risk of Amputation in Patients With Diabetes Mellitus and Peripheral Artery Disease," *Arteriosclerosis Thrombosis and Vascular Biology* 40, no. 8 (June 25, 2020): 1808–17, <https://doi.org/10.1161/atvbaha.120.314595>.

limb amputation compared with the general population and is a focus for worldwide patient care². In the United Kingdom (UK) there are approximately 75,000 prosthetic limb users, 60% of these are transtibial (below the knee) amputations³.

The WHO estimates 35–40 million people currently require prosthetic/orthotic services, with only 1 in 10 persons having access, most being in richer nations⁴. A significant global workforce shortfall exists in the field of prosthetics/orthotics, with a limited number of training programs worldwide^{5,6}. Prosthetic treatment spans a person's lifetime, with users receiving ongoing evaluation, provision of devices, maintenance, repair, and replacements over time. Statistics present the current unmet need and highlight the likelihood of significant underservicing of those who require prosthetic care.

Arguably, the most important aspect of a prosthetic limb is the socket fit, which provides the interface between the limb user and the prosthesis. Poorly fitting sockets cause pain, tissue breakdown, and reduced activity. To design an appropriately fitting socket that provides the user with comfort and functionality, the shape of the person's limb must be captured accurately and reliably.

Traditionally, when a person is deemed to need a new artificial limb, their residual limb is cast to capture the shape (Figure 1).



Figure 1: Conventional transtibial residual limb shape capture using Plaster of Paris.

As the shape is captured in an unloaded condition, the cast must be filled and modified in a laborious fashion by a skilled artisan clinician. It is not possible to routinely accurately measure the loaded shape of the residual limb in clinic. No record of the volume, circumferential, or diameter measures is currently possible in a controlled repeatable way. Such measurements are taken using simple tape measures and diameter sticks and are prone to be inaccurate, which in turn leads to multiple reworkings.

²World Health Organization: WHO. "Diabetes," November 14, 2024. <https://www.who.int/news-room/fact-sheets/detail/diabetes>.

³F. Davie-Smith and H. Scott, "The Scottish Physiotherapy Amputee Research Group (Sparg)," *Physiotherapy* 101 (May 1, 2015): e300–301, <https://doi.org/10.1016/j.physio.2015.03.496>.

⁴World Health Organization: WHO. "Assistive Technology," January 2, 2014. <https://www.who.int/news-room/fact-sheets/detail/assistive-technology>.

⁵United Nations. "Convention on the Rights of Persons with Disabilities CRPD) | Division for Inclusive Social Development (DISD)," n.d. <https://social.desa.un.org/issues/disability/crpd/convention-on-the-rights-of-persons-with-disabilities-crpd>.

⁶World Health Organization: WHO. WHO Standards for Prosthetic and Orthotics, 2017. <http://apps.who.int/iris/bitstream/10665/259209/1/9789241512480-part1-eng>.

Modification has demonstrated variable results between and within clinicians (Figure 2)⁷. The resulting socket fit is variable and may result in pain, skin breakdown, and socket refit. Additional appointments are inconvenient for prosthetic users as they are inefficient to clinical services and may result in increased travel (increasing environmental impact) and waste of materials should socket remakes be required⁸.



Figure 2: Conventional transtibial residual limb shape modification using Plaster of Paris.

Pressure systems using air and water are commonly used to capture shape to simulate loaded conditions. Shapes captured under pressurised conditions have demonstrated the creation of prosthetic sockets with lower peak pressures in a more repeatable manner with no modification required (Figure 3)⁹. Current pressure systems use traditional messy Plaster of Paris or expensive direct socket manufacture techniques to capture shape.



Figure 3: Pressure casting transtibial residual limb shape capture using Plaster of Paris (Ossur Icecast™).

Computer-aided design (CAD) scanners may also be used to capture the shape of the residual limb (Figure 4). Currently, CAD systems are generally handheld and require considerable practitioner skill and time. Although these systems are highly accurate, they replicate the process of capturing the limb

⁷Nadhira Al Shuaili et al., “Transtibial Prosthetic Socket Design and Suspension Mechanism: A Literature Review,” *JPO Journal of Prosthetics and Orthotics* 31, no. 4 (2019): 224–45, <https://doi.org/10.1097/jpo.0000000000000258>.

⁸Eddie Suyi Yang, Navid Aslani, and Anthony McGarry, “Influences and Trends of Various Shape-capture Methods on Outcomes in Trans-tibial Prosthetics,” *Prosthetics and Orthotics International* 43, no. 5 (2019): 540–55, <https://doi.org/10.1177/0309364619865424>.

⁹Mohammad Reza Safari and Margrit Regula Meier, “Systematic Review of Effects of Current Transtibial Prosthetic Socket designs—Part 2: Quantitative Outcomes,” *The Journal of Rehabilitation Research and Development* 52, no. 5 (January 1, 2015): 509–26, <https://doi.org/10.1682/jrrd.2014.08.0184>.

in a seated (unloaded) position. The shape obtained therefore requires further modification to ensure optimal prosthetic socket fit during standing and walking. Similar to traditional Plaster of Paris modification, time-consuming CAD adjustments made by individual clinicians are based on subjective interpretation and require substantial practitioner expertise.

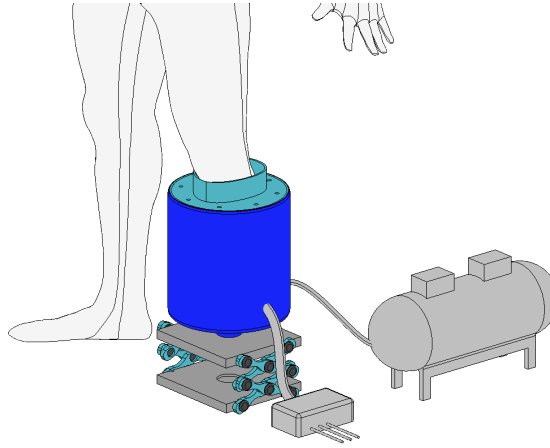


Figure 4: PCAD trans-tibial residual limb shape capture (Concept).

Although CAD and pressure systems are routinely used, these two methods have never been combined to capture the shape of a residual limb. The ability to achieve this in an automated manner would enable repeatable, quantified, loaded shape capture at lower cost and in less time, without the need for additional artisan modification. This would reduce costs for health services while providing improved fit and comfort for users.

An independent market report (Hauring-Medical-Management, 2020) was commissioned to assess the potential market for the PCAD™ system. Interviews were conducted with clinicians, sales representatives, and major commercial company executives. Consensus was highly positive regarding the potential of weight-bearing shape capture technology within this \$1.3 billion market. No competitor systems currently exist.

This paper describes the construction of a preliminary alpha prototype (PCAD™ system). The project involves design and build of a pre-commercial prototype PCAD™ system to satisfy MHRA regulatory requirements for a Randomised Control Trial in a prosthetic NHS centre in which a series of outcome measurements will provide a practical, clinical, and economic evidence bases to assist technique adoption.

Results and Discussion

PCAD™ has a simple concept: Scanning must be conducted under loaded conditions to avoid variable post-scan modification.

Patients insert their residual limb into a tank aperture between parallel bars. The unit is pressurised representing load (Figure 4).

The prosthetist presses a button on the keyboard or screen, initiating multiple scanners that capture the residual limb in 2–3 seconds. A CAD file is reconstructed on-screen, the tank is depressurised, and the patient removes their residual limb. As no modification of the scan is required, an MPEG/JPEG file is

displayed to the clinician and patient to confirm that the shape has been accurately captured. A hidden STL file is then sent to an approved PCAD™ manufacturer for prosthetic socket production. Using approved manufacturers allows economies of scale, reducing per-limb costs and ensuring consistent quality. Cost savings are passed to clinics, supporting economical purchasing while maintaining a sustainable business model.

By combining pressure and CAD technologies, PCAD™ enables efficient, automated socket fitting, delivering enhanced comfort and reduced pain for patients. The system can be used by clinicians at all levels, providing a consistent measurement process that produces sockets correctly fitted on the first attempt, without variable modification stages. PCAD™ has the potential to improve overall industry performance and standardisation among clinicians and is fully compatible with centralised fabrication of sockets using traditional or additive manufacturing techniques, thereby improving quality and reducing costs (Figure 5). Central manufacture ensures quality, consistency, and significant cost savings. Centralised data further enable analysis and continuous improvement of fit as PCAD™ learns from a large dataset of scans and prosthetic fittings.

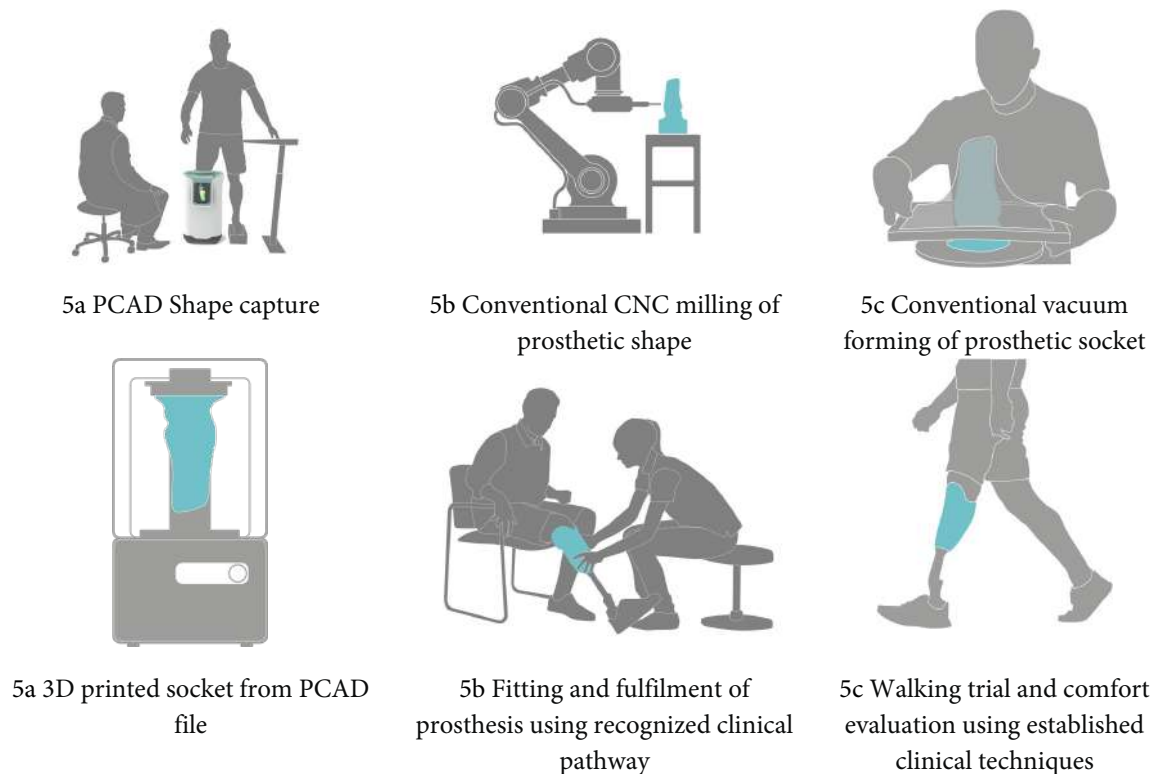


Figure 5: PCAD patient journey within established clinical pathways.

As can be seen from the workflow diagram in Figure 5, the PCAD system not only fits with existing clinical pathways, it also removes some steps and therefore reduces the time to achieve an accurate residual limb capture. This is valuable for prosthetic clinics and for patients. Our innovation, therefore, has real tangible economic, patient care, and healthcare delivery benefits and efficiencies.

PCAD has already progressed early laboratory R&D limb scanning concept (TRL3), through a functional “looks like” alpha prototype (TRL4), a de-risked System Architecture prototype (TRL5), and recently completed development of a fully functional Clinical Investigation prototype (TRL6).

The clinical trial unit was successfully built to exacting ISO approvals standards, and tested on patients during an approved Health Research Authority (HRA) Formative User Study in June 2025. The pilot clinical investigation study was undertaken at the Leeds prosthetic teaching hospital, in partnership with Steeper Group, one of the largest NHS providers. The investigation demonstrated to ability to scan, measure, and fit custom prosthetic sockets and that PCADs scanning unit could fit within existing workflows to improve clinic efficiency.

The study involved six patients in a randomised controlled trial and evaluated the performance of the PCAD scanning system compared with conventional unloaded CAD methods that required onscreen modification. Patients were scanned using both a currently used scanner (Biosculptor™) and a novel automated scanner (PCAD) and randomly allocated a prosthetic socket created by one or other methods.

Results demonstrated considerable potential for time savings with accurate scanning when using the PCAD system. Further technical refinement is needed to optimise the sealing process and height adjustment mechanism in order to enhance user experience, improve the process of physical entry to the system, and improve scan quality and efficiency. Funding has been secured to advance these developments (TRL 6/7) within the medical device regulatory framework (Figure 6).



Figure 6: PCAD transtibial residual limb shape capture clinical investigation.

PCAD technology will facilitate service delivery worldwide where the scanner can be used in-situ in different locations for limb shape capture and the data file sent for socket production within existing external manufacturing sites in centralised manufacturing hubs. The service then has the potential to

be offered in many locations where the rates of amputation are increasing and where services are not currently available.

Intellectual Property

PCAD's operations are founded on a defined Intellectual Property (IP) strategy. Core Background IP (BIP), owned by the University of Strathclyde, will be licensed to PCAD alongside relevant know-how. Key assets have been filed, with prosecution in progress and an EU patent granted.

The patented PCAD™ shape capture technique enables efficient, loaded scanning of residual limbs, producing accurate, modifiable-free data and facilitating longitudinal monitoring. This innovation enhances prosthetic fit quality and provides a basis for broader clinical applications, including diabetic and vascular volume assessment and orthotic scanning.

Conclusion

By shifting from plaster casting to digitally enabled workflows captured under loaded conditions, prosthetic provision can become more efficient, more affordable and more accessible, ultimately improving comfort and outcomes for patients while enhancing productivity for clinicians. PCAD has been conceived and invented for this purpose. Realising this digital future has the potential not only to transform prosthetic care delivery but also to narrow longstanding inequities in global access.

Acknowledgements

The PCAD project team gratefully acknowledges the invaluable support and expert guidance received from the Fédération Internationale de l'Automobile Foundation; Grid-4-Good; Scottish funding Council; Scottish Enterprise; Steeper and the University of Strathclyde.

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Chapter 10

PermeaSense: Rethinking How We Test Antimicrobials in the Fight Against Biofilm Infections

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Abstract

Antibiotic resistance is a growing global health crisis, projected to cause 10 million deaths annually by 2050. A central driver is the persistence of biofilms, which are structured bacterial communities encased in a protective matrix that make bacteria up to 1000 times more tolerant to antimicrobials. This resilience complicates infection treatment and industrial decontamination, contributing to economic losses estimated at \$1.2 trillion annually.

Current antimicrobial testing methods do not fully capture the spatial complexity of biofilms. They rely on bulk averages that mask tolerant sub-regions and do not resolve the matrix's contribution to limited penetration. This lack of resolution hinders the rational design of anti-biofilm therapies.

To overcome these limitations, we developed *PermeaSense*, a microfluidic platform that cultivates biofilms on engineered membranes and integrates mechanical sensing with optical microscopy to quantify drug penetration and matrix disruption in real time. Unlike conventional assays, *PermeaSense* generates spatial susceptibility profiles, revealing where treatments fail within biofilms.

We validated the system across diverse bacterial species and environmental conditions relevant to healthcare and industry. Results show that biofilm composition, architecture, and environment collectively shape permeability and antimicrobial efficacy. By providing mechanistic, reproducible insights into biofilm resilience, *PermeaSense* is designed to accelerate the development of next-generation therapies and optimised decontamination strategies. It offers a critical tool for bridging the gap between discovery and application, advancing efforts to mitigate antibiotic resistance and improve public health.

Keywords: *Biofilm, Antimicrobial tolerance, Drug testing platform, Spatial mapping*

Introduction

Bacterial biofilms, high density cell populations within a self-secreted polymer matrix, are often portrayed as impermeable fortresses, but their contribution to antimicrobial resistance is more nuanced. Many antibiotics can diffuse through the extracellular matrix, yet their effective concentration is reduced by binding or inactivation within the matrix polymers that also generates sharp gradients in oxygen and nutrients, creating metabolically inactive zones where drugs that rely on active growth, such

as β -lactams or fluoroquinolones, are inherently less effective¹. Coupled with stress responses, persister formation, and enzyme-mediated collective defences, biofilms form reservoirs of tolerant cells that sustain chronic infections and recurrent industrial contamination². While the oft-cited “100–1000 $\times$ tolerance” is context-dependent, the practical reality is clear: biofilms increase treatment failure, relapse, and control costs.

Measuring drug penetration into biofilms is therefore vital, not because penetration alone explains tolerance, but because it separates chemical exclusion from physiological tolerance as causes of failure. This distinction is critical for rational therapy design³. For small-molecule antibiotics, mapping penetration clarifies whether poor outcomes arise from diffusion barriers or metabolic heterogeneity. For newer modalities such as peptides, enzymes, nanoparticles, and phages, penetration is often the dominant bottleneck⁴. Quantitative penetration profiling also enables rational design of combination strategies, such as pairing matrix-disrupting agents with antibiotics, replacing trial-and-error with evidence-based approaches⁵.

Despite advances, antibiotic discovery faces a persistent translation gap: compounds that succeed in vitro often fail in vivo, especially in biofilm-associated infections⁶. Gold-standard minimum inhibitory concentration (MIC) and minimum biofilm concentration (MBC) assays measure activity in planktonic cultures but offer no insight into structured environments⁷. Commercial biofilm assays, such as MBEC plates, capture tolerance but reduce complex biology to a single endpoint⁸. Advanced flow cells and confocal imaging provide mechanistic detail, yet they are slow, operator-dependent, and too low-throughput for iterative pipelines⁹. Developers are left choosing between speed without inference or depth without scalability.

¹Jeanyoung Jo, Alexa Price-Whelan, and Lars E.P. Dietrich, “Gradients and Consequences of Heterogeneity in Biofilms,” *Nature Reviews Microbiology* 20 (2022): 593–607, <https://doi.org/10.1038/s41579-022-00692-2>

²Ho Yu Liu, Emma L. Prentice, and Mark A. Webber, “Mechanisms of Antimicrobial Resistance in Biofilms,” *Npj Antimicrobials and Resistance* 2, no. 27 (2024), <https://doi.org/10.1038/s44259-024-00046-3>

³Andy Y. An et al., “An Overview of Biological and Computational Methods for Designing Mechanism-Informed Anti-Biofilm Agents,” *Frontiers in Microbiology* 12 (2021): 640787, <https://doi.org/10.3389/fmicb.2021.640787>

⁴Cesar Augusto Roque-Borda et al., “Antimicrobial Peptides: A Promising Alternative to Conventional Antimicrobials for Combating Polymicrobial Biofilms,” *Advanced Science* 12, no. 1 (2024): e2410893, <https://doi.org/https://doi.org/10.1002/advs.202410893>

⁵Ergun Akturk et al., “Combining Phages and Antibiotic to Enhance Antibiofilm Efficacy against an in Vitro Dual Species Wound Biofilm,” *Biofilm* 6 (2023): 100147, <https://doi.org/10.1016/j.biofilm.2023.100147>

⁶Tom Coenye et al., “Global Challenges and Microbial Biofilms: Identification of Priority Questions in Biofilm Research, Innovation and Policy,” *Biofilm* 8 (2024): 100210, <https://doi.org/10.1016/j.biofilm.2024.100210>

⁷Amber De Bleckere et al., “High Throughput Determination of the Biofilm Prevention Concentration for *Pseudomonas Aeruginosa* Biofilms Using a Synthetic Cystic Fibrosis Sputum Medium,” *Biofilm* 5 (2023): 100106, <https://doi.org/10.1016/j.biofilm.2023.100106>

⁸Kristina Ivanova et al., “Integrated Biofilm Dispersion and Virulence Responsiveness for Targeted Treatment of *Pseudomonas Aeruginosa* Infection in Lungs,” *Advanced Functional Materials* 34, no. 46 (2024), <https://doi.org/10.1002/adfm.202402868>

⁹Yuzhen Zhang et al., “A Microfluidic Approach for Quantitative Study of Spatial Heterogeneity in Bacterial Biofilms,” *Small Science* 2, no. 10 (2022): 2200047, <https://doi.org/10.1002/smssc.202200047>

This mismatch creates bottlenecks: lack of mechanistic feedback during optimisation, poor reproducibility from heterogeneous growth, and a persistent throughput–realism trade-off. Without tools to resolve whether drug failure stems from penetration limits or physiology, optimisation remains empirical, and regulatory progress slows.

PermeaSense aims to address this gap by leveraging a microfluidic platform that delivers real-time, spatially resolved data on penetration and efficacy. By standardising biofilm growth on engineered membranes, it produces predictable architectures and gradients that mimic clinically relevant states. Integrated flow control and optical sensing enable label-free monitoring, distinguishing penetration-limited from physiology-driven failure. Positioned as a mid-pipeline tool, *PermeaSense* complements rather than replaces existing assays, accelerating lead optimisation, guiding rational combination design, and generating mechanistic datasets suitable for AI-driven pipelines.

Results and Discussion

We developed a tuneable microfluidic membrane platform that enables reproducible biofilm growth, continuous measurement of permeability, and subsequent assessment of compound penetration within the same system (Figure 1a). The system integrates an optically transparent microchannel with an embedded porous membrane that supports uniform biofilm growth while allowing continuous in-plane imaging. A dynamic flow environment, simulating both constant and fluctuating conditions, is controlled via a pressure modulator, while an array of flow sensors records membrane flux to calculate permeability. Together, these features eliminate the need for confocal sectioning and enable simultaneous monitoring of biofilm structure and transport dynamics, overcoming the reproducibility challenges that limit conventional assays.

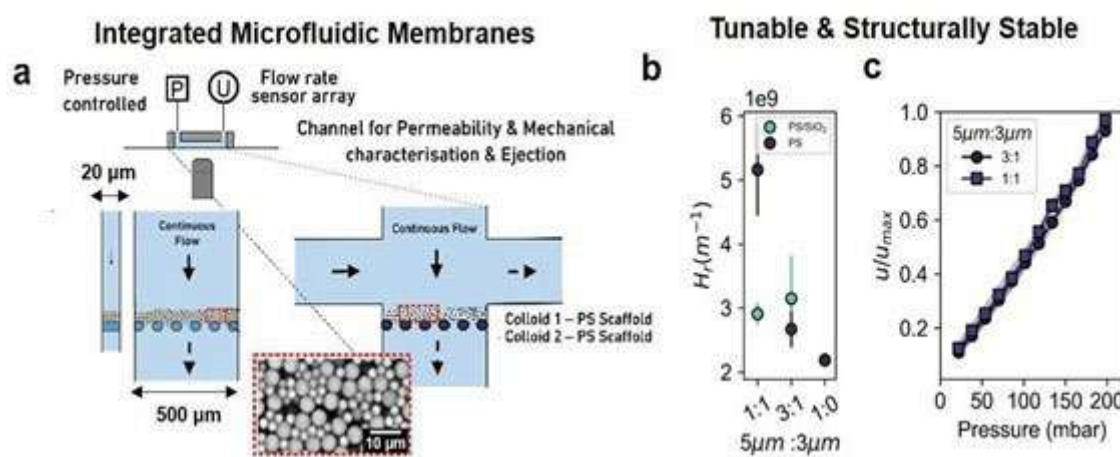


Figure 1: Development of Permeasense microfluidics incorporating in-situ flow assembled colloidal membranes. (a) Top view of the key microfluidic innovation. After membrane formation (inset) the device is sintered to produce a mechanically stable membrane. Black arrows indicate the flow direction. (b) The hydraulic resistance (H_r) of the microfluidic membranes tuned by adjusting the volume ratio of colloids and their material composition. (c) Linear pressure ramps with outlet velocity indicates compliance with Darcy's law.

The membranes are fabricated by trapping and sintering colloidal particles within a microstructured pillar array, producing stable porous substrates whose geometry and hydraulic resistance can be precisely tuned (Figure 1b). By selecting particle size and composition, we generated pore structures

that exclude bacterial penetration. Validation experiments confirmed mechanical robustness (Figure 1c). These tests confirmed the membranes provide a reliable reference material for biofilm permeability studies.

When inoculated with bacteria, the membranes reproducibly supported biofilm attachment and expansion (Figure 2a). In *Staphylococcus epidermidis*, biofilm growth produced a gradual decline in flux, culminating in complete channel occlusion after approximately 6.5 hours. Time-lapse imaging and segmentation enabled direct correlation of structural growth with hydraulic resistance (Figures 2b, c). We imposed various pressure regimes that can mimic physiological fluid dynamic environments, and showed biofilm hydraulic resistance was invariant across physiologically relevant pressures (Figure 2d).

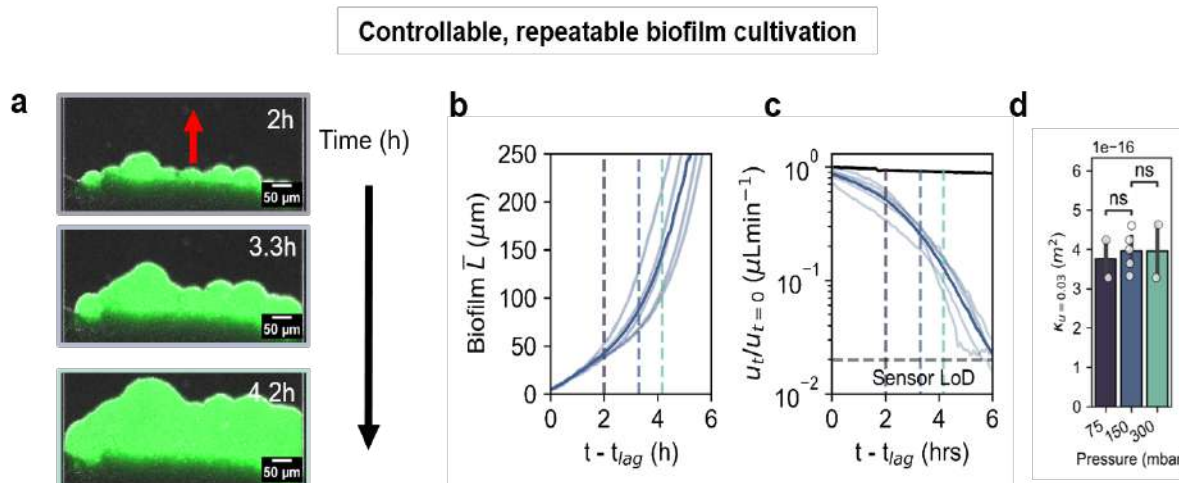


Figure 2: Quantifying real-time biofilm hydraulic permeability using Permeasense (a) Representative epifluorescent micrographs *S. epidermidis* 1457 biofilm growth upon the membrane substrate. The coloured frames denote the time slice from the subsequent dashed lines plots. (b) Biofilm development is tracked by measuring the biofilm thickness using time lapse microscopy. (c) Microfluidic flow sensors measure the flow rate (u) at the channel outlet, enabling the calculation of permeability. The black curve denotes control experiments performed with sterile media (d) Biofilm hydraulic resistance (H_r) and permeability (κ) are invariant under varying hydrostatic.

The platform enabled matrix compositional and environmental perturbations to be directly linked to permeability (Figure 3a). In *S. epidermidis*, *Escherichia coli*, and *Bacillus subtilis* mutants lacking key matrix polysaccharide components produced significantly more permeable biofilms (Figure 3b). Nutrient composition further modulated structure: substrate-limited conditions significantly reduced biofilm permeability, underscoring how global metabolic state shapes matrix transport properties. Extending this approach to multiple species, including *Pseudomonas aeruginosa* and *Burkholderia cenocepacia*, revealed that increasingly pathogenic biofilms have lower matrix permeability (Figure 3c). These comparisons highlight the platform's utility as a standardised assay for cross-species benchmarking of biofilm permeability and structure.

Building on this foundation, we developed an antibiotic assay that leverages the membrane architecture to provide spatially resolved efficacy profiles. Biofilms are first cultivated to predefined thicknesses, while optical flow analysis continuously tracks biofilm expansion across its depth (Figure 4a). Then, antimicrobial compounds are administered. Local shifts in expansion rates reveal how efficacy varies with biofilm thickness, while complementary staining with extracellular DNA markers captures the

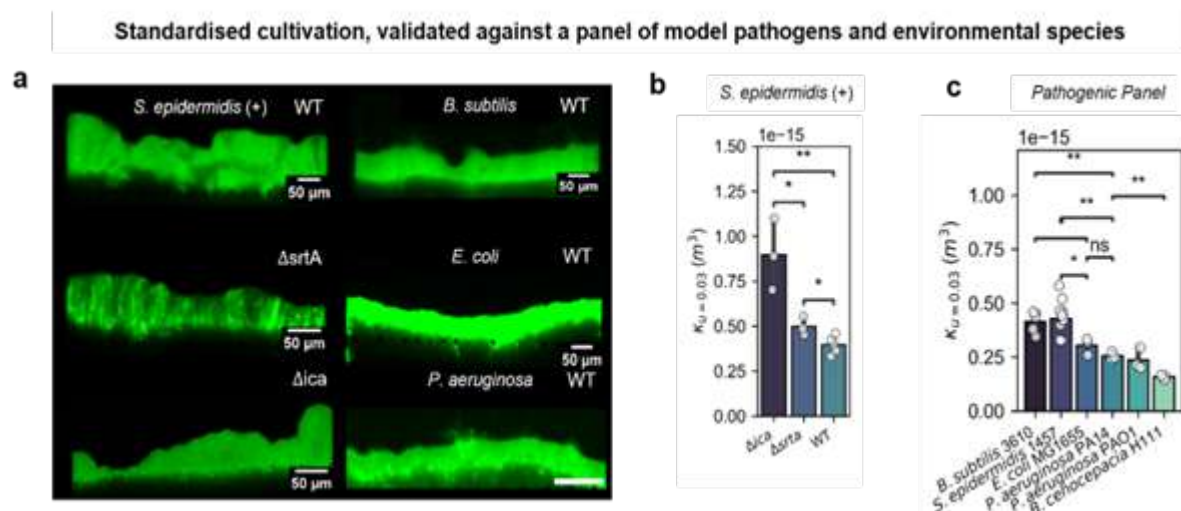


Figure 3: Permeasense is species agnostic and reveals that polysaccharide extracellular matrix components significantly contribute to biofilm permeability across multiple model biofilm species (a) Representative epi-fluorescence images of environmental and pathogenic biofilms (b) Permeability plots of *S. epidermidis* biofilm grown in kinetically limiting conditions. (c) Permeability plot overview of pertinent pathogens.

progression of cell death through successive layers (Figure 4b). The combined readout produces a quantitative penetration-depth metric that directly links compound activity within the biofilm architecture, distinguishing penetration-limited effects from physiological tolerance. This approach moves beyond endpoint survival measurements by providing a mechanistic, real-time view of how antimicrobials act within structured microbial communities.

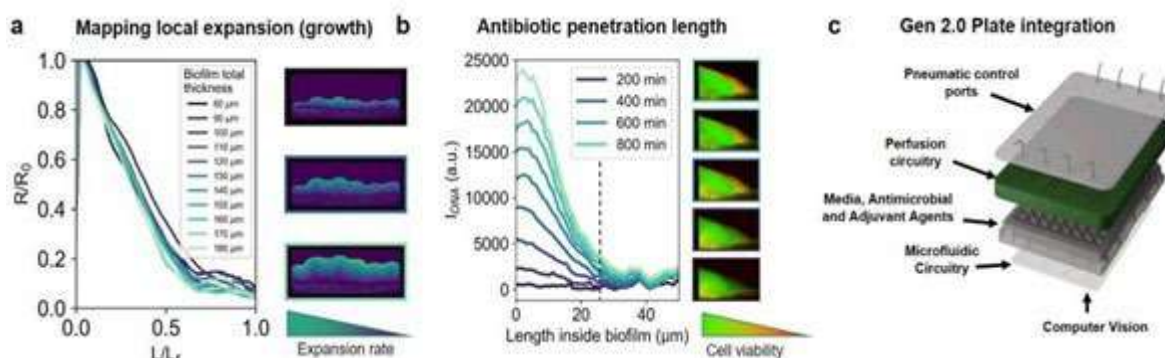


Figure 4: Parallelising the Permeasense technology for high throughput antibiotic penetration profiling (a) Optical flow analysis determines localised growth rates through the biofilm thickness (b) Integrated fluorescence imaging of eDNA release maps the activity and penetration upon antibiotic exposure (vancomycin 3 μ g/ml vs *S. epidermidis*). (c) Schematic of Gen 2.0 platform integrated into a microtitre plate configuration.

To enhance throughput and usability, the platform is being scaled to incorporate 20 parallel channels via pneumatic microfluidic switches (Figure 4c). Our 2.0 design preserves the analytical power of the original device while enabling parallel testing of compound panels. A further iteration is focused on minimising operator expertise. By embedding the microfluidic circuitry into a standard microtitre plate format, the system will align with familiar laboratory workflows: users will load wells with growth media, inoculum, and candidate antimicrobials, while an integrated manifold manages flow control and optical sensing. This format not only lowers the barrier to adoption but also positions the system for integration into automated discovery pipelines.

Conclusion

Collectively, these results demonstrate a platform that provides a robust, tuneable, and reproducible method for quantifying biofilm permeability and antimicrobial penetration in situ. Unlike conventional assays that yield only average endpoint values, the platform delivers continuous, mechanistic datasets that resolve where and why treatment fails. Its reproducibility makes it suitable for standardised use, while its mechanistic richness provides the kind of labels suitable for AI-driven design. Positioned as a mid-pipeline tool, *PermeaSense* bridges the translational gap that often causes promising compounds to fail in vivo. By providing clarity on compound penetration, tolerance, and combination effects in a scalable and user-friendly format, the platform offers a pathway for accelerating next-generation antimicrobial discovery and regulatory validation.

Acknowledgements

The authors thank Dr. Jeremy Wong for valuable discussions. The authors acknowledge financial support from SNSF PRIMA grant 179834 (to E.S.), MSCA individual fellowship grant 101033169 and SNSF Bridge Proof of Concept Grant 222403 (to S.C.).

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Chapter 11

Nano Plants (Nanostructured Implants)

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Abstract

Aesthetic/medical considerations often motivate individuals to seek treatments that enhance dental appearance. However, the high cost of dental implants can discourage many patients from pursuing such procedures. A similar situation arises with ceramic hip, knee, and shoulder implants, which are associated with substantial financial burden. In addition to cost concerns, zirconia-based ceramic implants are susceptible to degradation through Hydrothermal Ageing (HTA), a well-documented limitation that affects their long-term performance and reliability.

At Loughborough University, we have investigated the processing of nanocrystalline-ceramic powders into useful biomedical implants via several projects each focusing on a different stage of the manufacturing route viz., (i) the ability to control the agglomerates for achieving flowable-and-crushable powder for die pressing, (ii) the formation of low viscosity but high-solids-content suspensions suitable for 3D printing, and (iii) the use of sustainable microwave-assisted sintering techniques. This holistic approach helped to reduce material wastage, energy consumption, and carbon emission during implant manufacturing.

We developed various nanostructured zirconia-based ceramic components exhibiting vastly superior HTA resistance (>700 times improvement over conventional counterparts) and mechanical performance suitable for use as biomedical implants for dental and hip/knee prosthesis. This will directly impact the >£40B worldwide dental and orthopaedics market through ever-lasting implants and will provide better quality-of-life for the ageing population of around 3 billion people across the globe. The 3D-printed hydrothermally immune dental implants was considered as one of the six best modern technological developments in materials science for shaping the future by a BBC documentary, titled *Materials for the Modern Age: The Secret Story of Stuff*.

Keywords: 3D Printing, Biomedical Implants, Nanostructured Ceramics, Microwave Sintering, Hydrothermal Ageing

Introduction

From dinner plates to rocket nozzles and aeroengines to electronic packaging, ceramics are ubiquitous in our daily lives. Ceramic materials are classified based on their composition, characteristics, and applications. While ceramics exhibit a wide range of physical and chemical properties that make them suitable for many applications, advanced ceramics that are bio compatible and are specifically developed

for the biomedical implants are classified as bioceramics. Bioceramic implants are typically used for dental restorations, hip and knee prosthesis, finger joints, and bone tissue engineering/scaffolding and are predominantly made of yttria stabilised zirconia (YSZ) and zirconia-toughened-alumina (ZTA) ceramics. Currently 61% of hip joint replacements are for the 65+ age group and 36% are at 45–64, figures in both age categories are set to rise as people live longer and younger people are increasingly willing to pay for operations that allow them to enjoy sports that place a strain on joints for longer. A closer inspection of the global dental and orthopaedic market data suggests that the USA, Europe, and Japan account for 80% of the market, even though from a population perspective, these regions make up just 20% of the eight billion world population. This illustrates the huge global growth potential in this area: as the standard of living in India, China, Africa, and other regions rise, so will the demand for joint replacement operations. Thus, there is growing demand for bioceramic implants with the ageing population across the globe and any improvement in the development or processing of these bioceramic materials that enhances the quality of the patient life will have tremendous social, economic, and environmental impact.

However, there are two major challenges associated with bioceramic implants manufacturing: (i) complex shaping and (ii) energy intensive sintering. The conventional subtractive implant manufacturing processes involving machining and polishing account for significant material's wastage, amounting to around 90% loss (Figure 1) in some cases, and these methods also pose an environmental concern (with fine particle debris floating around CNC machining/lathe equipment).

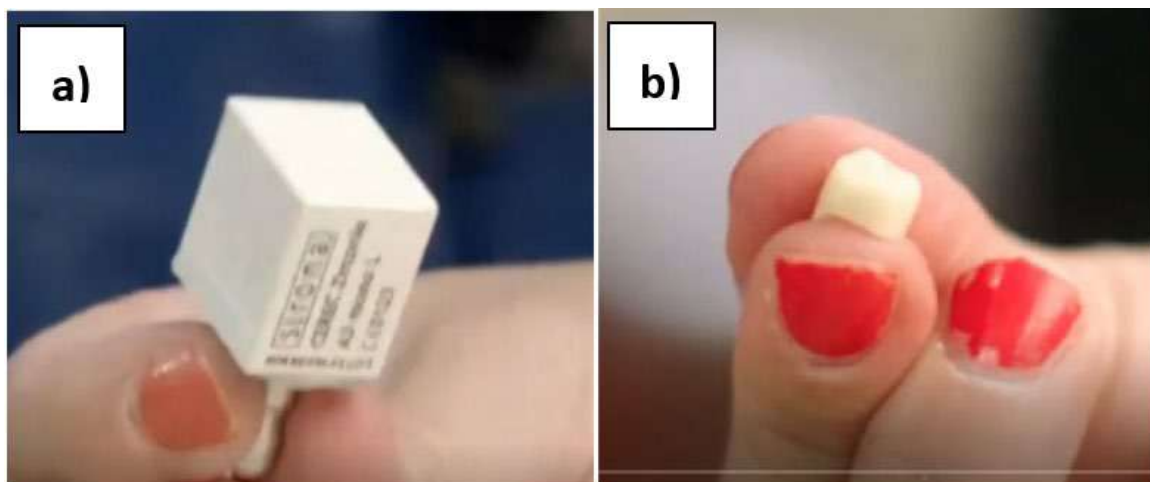


Figure 1: Conventional subtractive manufacturing of a ceramic dental crown: a) block of zirconia ceramic (15 grams) and b) machined ceramic crown (1.4 grams), resulting in significant material wastage.

Recently at Loughborough University (LU), additive manufacturing (AM, also known as 3D printing) is employed to make these advanced ceramic biomedical implants suitable for personalised healthcare solutions with unparalleled design complexities, allowing for near-net-shaping. Eco-friendly field assisted sintering technologies (FAST) such as microwave and hybrid sintering are used to reduce energy consumption during implant manufacture. A thoughtful combination of AM and FAST resulted in the development of affordable, patient-specific, vastly superior nanostructured ceramic implants with reduced material wastage, energy consumption, and carbon emissions. This forms the subject matter of this article.

Results and Discussion

Various research projects at LU over the years have delivered significant foreground intellectual property¹ and technology know-how related to the fabrication of nanostructured ceramic materials with outstanding properties, surpassing some of the commercial counterparts, relevant to the energy, electronic security and in particular healthcare sectors. Specifically, it has been demonstrated that the hydrothermal ageing (HTA) resistance of zirconia-based ceramics can be enhanced significantly² by retaining a nano grain size below 180 nm even at low density components. This is highly relevant to the approximately seven-billion-dollar hip replacement market where concerns about the toxicity/wear debris in metal and polymer components renders all-ceramic solutions increasingly attractive. HTA degradation (the unwanted conversion of tetragonal zirconia to a weaker monoclinic form in an aqueous environment) is the Achilles-heel for the use of zirconia ceramics in the biomedical sector and was the reason behind the well-publicised failure of zirconia hip replacements around the year 2000. Thus, when HTA is countered, new opportunities open. The LU developed technology involve production of novel nano-suspensions with controlled rheology suitable for 3D printing and the microwave-assisted sintering³ regimes for the manufacturing of zirconia and ZTA ceramics. This holistic powder-to-product approach delivered very small zirconia grain sizes that will assist current compliance (e.g. ISO 13356, ISO 633-3) and open up novel all-ceramic hip replacements via multi-fold enhancement in HTA-resistance of both porous and dense zirconia-based implant structures.

We have demonstrated using many 3D printing platforms like direct ink writing (DIW), digital light projection (DLP), stereolithography (SLA) that near net-zero manufacturing of bioceramic implants can be achieved with almost negligible material wastage, which is a welcoming sustainability trait. Our 3D printing processes use tailored ceramic ink formulations with desirable flow properties to build the complex implant structures directly from the design files (Figure 2, Figure 3, and Figure 4), which significantly reduces material wastage and production costs.



Figure 2: DIW 3D printed nanostructured YSZ dental components.

¹Annapoorani Ketharam et al. "Deformable granule production." UK Patent. 2013.

²Anish Paul, Bala Vaidhyanathan, and Jon G. P. Binner. "Hydrothermal Aging Behavior of Nanocrystalline Y-TZP Ceramics." *Journal of the American Ceramic Society* 94, no. 7 (2011): 2146–52. <https://doi.org/10.1111/j.1551-2916.2010.04341.x>

³Jon Binner and Bala Vaidhyanathan. "Processing of Bulk Nanostructured Ceramics." *Journal of the European Ceramic Society* 28, no. 7 (2008): 1329–39. <https://doi.org/10.1016/j.jeurceramsoc.2007.12.024>

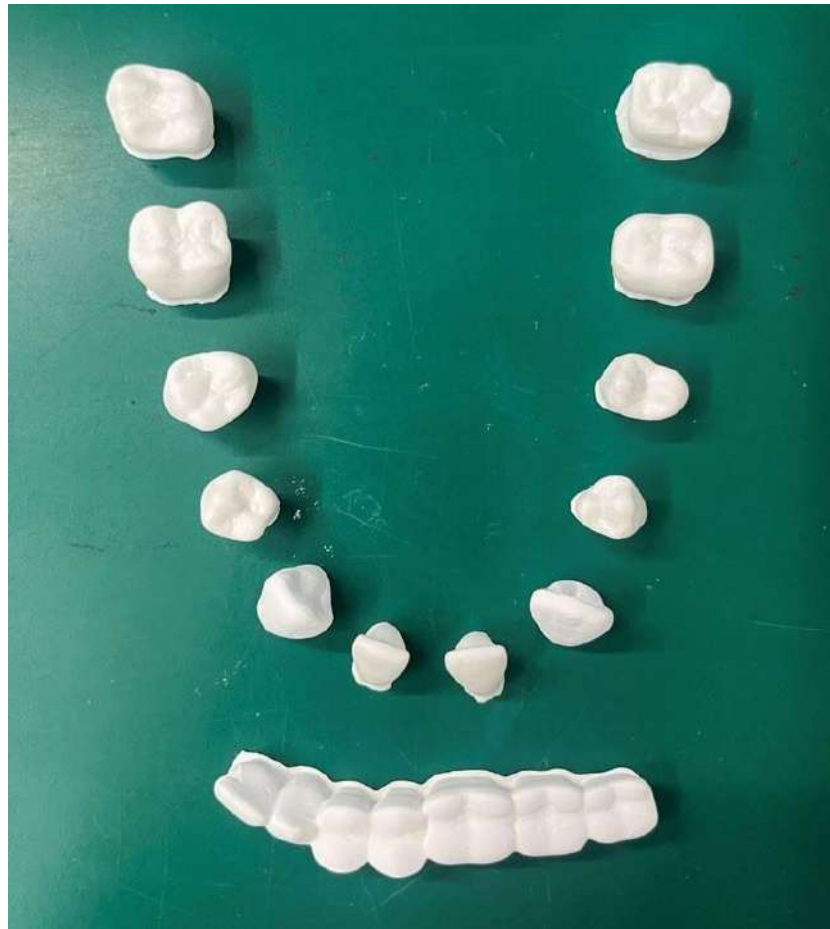


Figure 3: DLP 3D printed ceramic dental components.



Figure 4: DLP 3D printed ceramic hip implants: a) Femoral Head and b) Acetabular Cup.

The sintering step is the most energy-consuming step in any ceramic filter manufacturing process. Employing FAST like microwave processing at LU, the time and temperature required for sintering

have been reduced, which in turn cut down the energy consumption and the associated carbon emission.

Also, a combination of AM and FAST methodologies were employed for the first time to make sustainable ceramic implants with exemplary control on density, nano grain structure, porosity, pore morphology, and novel designed lattices, thus pushing the research boundaries on next generation bioceramic implant manufacturing. This resulted in ceramic implants with extremely fine-grained nanostructure (Figure 5) compared to conventionally processed YSZ ceramics. This exceptional nanostructure, resulted in complete stabilisation of the tetragonal structure for zirconia grains, resulting in total immunity towards HTA⁴. When compared with conventional methods, the 3D-printed YSZ structures also achieved 99.4 ± 0.2 % density and an average Vickers microhardness of $HV_{1/10} = 1244.2 \pm 98.2$ (equivalent to 12.2 ± 0.96 GPa)⁵.

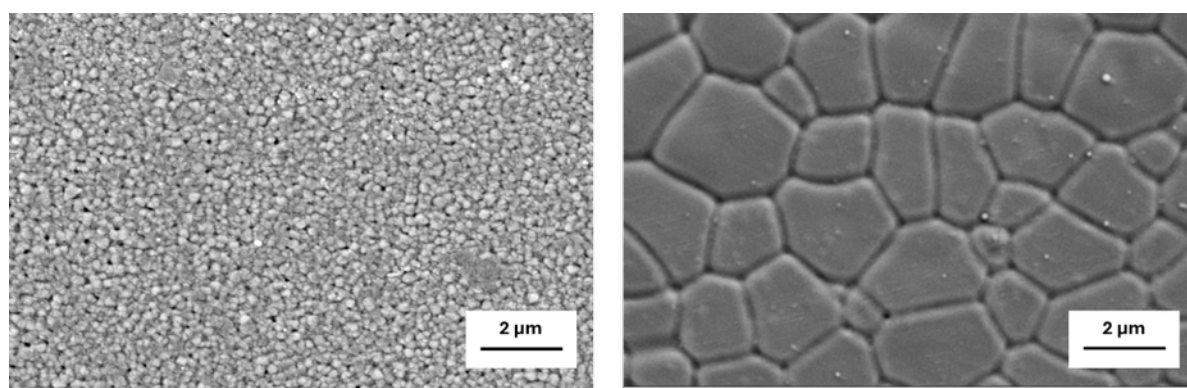


Figure 5: a) Nano grain structure using AM and FAST and b) Corresponding conventional micro grain structure of YSZ ceramics.

Further, our ceramic ink formulations are also adaptable for various 3D printing platforms, from cheap and cheerful (£200) desktop printers to the expensive, high throughput (£200,000) printers available to the industry. By adapting the bioceramic resin formulation, this research demonstrates, for the first time, that high-quality ceramic implants/components can be produced using accessible and cost-effective printers⁶. In doing so, it represents a step forward in the democratisation of additive manufacturing for functional ceramics, aiming to reduce barriers to entry and expand the potential for wider adoption of AM in various industrial and research applications. This will help to move the dial on the applicability of ceramic AM from a ‘high value – low volume’ technology to a ‘high volume – low value’ viable methodology for producing complex shaped ceramic components. By resorting to a large number of low-end 3D printers (rather than one or two high-end expensive printers), productivity/throughput can be enhanced without compromising on product quality. Such a trait

⁴Paul, Vaidhyanathan, and Binner, “Hydrothermal Aging Behavior of Nanocrystalline Y-TZP Ceramics,” March 2, 2011.

⁵Athanasios Goulas et al., “Formulation-driven Additive Manufacturing of 3YSZ Advanced Ceramics via Digital Light Processing,” *Open Ceramics* 22 (April 22, 2025): 100785, <https://doi.org/10.1016/j.oceram.2025.100785>

⁶Athanasios Goulas et al., “Enabling Accessible Additive Manufacturing of Alumina Ceramics Through Formulation Design,” *Materials & Design* 258 (August 18, 2025): 114601, <https://doi.org/10.1016/j.matdes.2025.114601>

augers well for the scale-up manufacturing of biomedical implants via ‘low cost – low wastage’ additive manufacturing and the industrial take-up of these emerging technologies to make ‘affordable’ all-ceramic implants.

In addition, 3D printing of biomedical implants also lends itself to remote manufacturing. Further, digitalization of product development and process control can be achieved through AI, neural networks, and machine learning algorithms, paving the way for next-generation implants via IR 4.0/5.0.

Conclusions

Zirconia-based bioceramic resin formulations were designed/developed that are suitable for 3D printing across many accessible and cost-effective DLP printer platforms to produce high-quality ceramic implants/components for healthcare applications. Field assisted sintering techniques were used to achieve fine grained ceramic structures that are totally immune to hydrothermal ageing. Thus, the unique combination of AM and FAST methodology was employed for the first time to make ceramic implants with exemplary control on density, nano grain structure, as well as superior performance, leading to next generation sustainable bioceramic implant manufacturing.

Acknowledgements

This work was funded by the UKRI through the Midlands Advanced Ceramics for Industry 4.0 Strength in Places Fund (82148). The authors acknowledge the use of the facilities in the Loughborough Materials Characterisation Centre (LMCC).

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Chapter 12

Artificial Intelligence and Quantum Computing for the Design of Novel Kisspeptin-10 Analogues and Their Experimental Evaluation in Cervical Cancer Cells

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Abstract

Cervical cancer remains a leading cause of morbidity and mortality in women, underscoring the need for innovative therapies. Kisspeptin-10 (KP10), a decapeptide that activates the G-protein-coupled receptor (GPCR) Kiss1R, shows antitumour potential. Using artificial intelligence (AI) based modelling, a focused library of KP10 analogues was designed; 10 top candidates were synthesised and evaluated. Molecular docking predicted enhanced Kiss1R affinity, which was confirmed in vitro by MTT and wound-healing assays in cervical cancer cells. Several analogues showed superior cytotoxicity and migration inhibition versus KP10. These results highlight AI-assisted peptide design as an efficient approach for developing GPCR-targeted therapeutics in cervical cancer.

Keywords: *Kisspeptin-10, Cervical cancer, GPCR, Artificial intelligence, Peptide design, Antitumour activity*

Introduction

Cervical cancer remains a major global health concern and one of the leading causes of cancer-related death among women, particularly in low- and middle-income countries. Despite progress in screening, vaccination, and treatment, many cases are diagnosed at advanced stages with poor outcomes, highlighting the need for new targeted therapies^{1,2}.

The kisspeptin system has recently gained attention beyond its reproductive role³. Kisspeptins, derived from the *KISS1* gene, include the potent fragment Kisspeptin-10 (KP10), which binds the G-protein-coupled receptor (GPCR) Kiss1R⁴. Initially identified for its antimetastatic properties in melanoma and

¹Marc Arbyn et al., “Estimates of Incidence and Mortality of Cervical Cancer in 2018: A Worldwide Analysis,” *The Lancet Global Health* 8, no. 2 (2020): e191–203, [https://doi.org/10.1016/s2214-109x\(19\)30482-6](https://doi.org/10.1016/s2214-109x(19)30482-6).

²World Health Organization: WHO, “Cervical Cancer,” December 2, 2025, <https://www.who.int/news-room/fact-sheets/detail/cervical-cancer>.

³Simina M. Popa, Donald K. Clifton, and Robert A. Steiner, “The Role of Kisspeptins and GPR54 in the Neuroendocrine Regulation of Reproduction,” *Annual Review of Physiology* 70 (2008): 213–38, <https://doi.org/10.1146/annurev.physiol.70.113006.100540>.

⁴Masato Kotani et al., “The Metastasis Suppressor Gene *KiSS-1* Encodes Kisspeptins, the Natural Ligands of the Orphan G Protein-coupled Receptor GPR54,” *Journal of Biological Chemistry* 276, no. 37 (2001): 34631–6, <https://doi.org/10.1074/jbc.m104847200>.

breast cancer⁵, kisspeptin signalling is now linked to key oncogenic processes such as proliferation, migration, angiogenesis, and apoptosis⁶. These findings support the exploration of kisspeptin analogues as therapeutic modulators, particularly in hormone-responsive and reproductive cancers like cervical cancer.

Artificial intelligence (AI) and machine learning have transformed peptide-based drug discovery by enabling rational design, predictive modelling, and efficient screening of large peptide libraries⁷. These tools accelerate the identification of bioactive sequences with favourable pharmacological profiles and guide experimental validation⁸.

This study applies AI-driven prediction and molecular docking to design and evaluate KP10 analogues with potential antitumour activity. Ten top-scoring peptides were synthesised and tested for cytotoxic and anti-migratory effects in cervical cancer cells, establishing a framework for AI guided GPCR targeted peptide discovery in oncology.

Results and Discussion

AI-based prediction of KP10 analogues

KP10 analogues were rationally designed through an AI-driven workflow to identify variants with improved antitumour potential. Starting from the native sequence (YNWNSFGLRF), over 5000 analogues were generated via Python-based systematic mutations and extensions (10–12 amino acids). Each sequence was encoded with 1477 physicochemical descriptors from Propy 1.0⁹, and filtered by charge, hydrophobicity, molecular weight, and complexity, yielding 70 biologically plausible candidates. These were evaluated using three machine-learning classifiers: SVM, Random Forest, and ANN, trained on balanced anticancer peptide datasets. Consensus predictions identified the most robust candidates for subsequent structural modelling and biological testing.

In silico prediction of antitumour potential

The antitumour potential of 70 KP10 analogues was assessed using the MLACP 2.0 server¹⁰, which applies physicochemical descriptors and machine learning algorithms (LightGBM, Extra Trees) trained

⁵Jeong-Hying Lee et al., “KiSS-1, a Novel Human Malignant Melanoma Metastasis-Suppressor Gene,” *JNCI Journal of the National Cancer Institute* 88, no. 23 (1996): 1731–7, <https://doi.org/10.1093/jnci/88.23.1731>.

⁶Saima Jabeen et al., “Kisspeptin Mediated Signaling in Cancer,” *Current Topics in Medicinal Chemistry* 16, no. 22 (2016): 2471–6, <https://doi.org/10.2174/1568026616666160212123309>.

⁷Silong Zhai et al., “Artificial Intelligence in Peptide-based Drug Design,” *Drug Discovery Today* 30, no. 2 (2025): 104300, <https://doi.org/10.1016/j.drudis.2025.104300>.

⁸Kathy Sharon Isaac et al., “Machine Learning Tools for Peptide Bioactivity Evaluation – Implications for Cell Culture Media Optimization and the Broader Cultivated Meat Industry,” *Current Research in Food Science* 9 (2024): 100842, <https://doi.org/10.1016/j.crfs.2024.100842>.

⁹Dong-Sheng Cao, Qing-Song Xu, and Yi-Zeng Liang, “Propy: A Tool to Generate Various Modes of Chou’s PseAAC,” *Bioinformatics* 29, no. 7 (2013): 960–2, <https://doi.org/10.1093/bioinformatics/btt072>.

¹⁰Le Thi Phan et al., “MLACP 2.0: An Updated Machine Learning Tool for Anticancer Peptide Prediction,” *Computational and Structural Biotechnology Journal* 20 (2022): 4473–80, <https://doi.org/10.1016/j.csbj.2022.07.043>.

on validated anticancer peptide datasets. Peptides with high-confidence anticancer predictions were prioritised. This two-tiered strategy (AI classifiers optimised for HeLa cytotoxicity followed by external ACP validation) strengthened candidate selection for molecular docking and experimental evaluation. See Table 1.

Table 1: List of designed analogues, including MLACP 2.0 prediction scores and consensus annotations.

Peptide	Sequence	Length (aa)	Net Charge	MW (Da)	MCLAP Score
KP10	YNWNSFGLRF	10	+2.0	1302.45	0.833
KP10-01	YNWNTFGLRF	10	+2.0	1316.48	0.848
KP10-02	YNWNSFSLRF	10	+2.0	1332.48	0.893
KP10-03	YNWNSFGIRF	10	+2.0	1302.48	0.887
KP10-04	YNFWNSFGLRF	11	+2.0	1449.63	0.880
KP10-05	YDWNSFGLRF	10	+1.0	1303.44	0.877
KP10-06	YNWNSWGLRF	10	+2.0	1341.49	0.843
KP10-07	YNFNSFGLRF	10	+2.0	1263.42	0.836
KP10-08	YNWNSFGLRW	10	+2.0	1341.49	0.828
KP10-09	YNWNSFGQLRF	11	+2.0	1430.58	0.819
KP10-10	YNWNSFGVRF	10	+2.0	1288.43	0.815

Molecular docking simulations and binding affinity estimations

Molecular docking simulations were conducted using HPEPDOCK 2.0¹¹ to assess receptor binding of KP10 analogues. All peptides showed negative docking scores, indicating favourable interactions. Native KP10 exhibited a score of −298.2, while most analogues ranged from −257.1 to −287.7; KP10-01 and KP10-06 showed comparable affinities. Binding free energies (ΔG) and dissociation constants (K_d) estimated with PRODIGY¹² supported these results, with KP10-05, KP10-06, KP10-09, and KP10-10 displaying lower ΔG values (−9.3 to −8.8 kcal/mol) and submicromolar K_d ($\approx 10^{-7}$ M) versus KP10 (ΔG = −7.5 kcal/mol; K_d = 4.8×10^{-6} M) (See Table 2). These findings indicate that specific sequence modifications improve peptide receptor interactions and guided analogue prioritisation for synthesis and biological testing.

Table 2: Predicted binding affinity of KP10 analogues to the receptor target based on molecular docking simulations.

Peptide	Docking Score	ΔG (kcal/mol)	K_d (M)
KP10	-298.2	-7.5	4.8×10^{-6}
KP10-01	-287.7	-6.2	4.2×10^{-5}
KP10-02	-275.1	-6.8	1.6×10^{-5}
KP10-03	-265.9	-7.8	3.1×10^{-6}
KP10-04	-257.1	-8.3	1.3×10^{-6}
KP10-05	-264.6	-9.3	2.9×10^{-7}

¹¹Pei Zhou et al., “HPEPDOCK: A Web Server for Blind Peptide–protein Docking Based on a Hierarchical Algorithm,” *Nucleic Acids Research* 46, no. W1 (2018): W443–50, <https://doi.org/10.1093/nar/gky357>.

¹²Li C. Xue et al., “PRODIGY: A Web Server for Predicting the Binding Affinity of Protein–protein Complexes,” *Bioinformatics* 32, no. 23 (2016): 3676–8, <https://doi.org/10.1093/bioinformatics/btw514>.

Table 2: Continued.

Peptide	Docking Score	ΔG (kcal/mol)	Kd (M)
KP10-06	-286.3	-9.3	2.8x10 ⁻⁷
KP10-07	-273.1	-5.8	8.7x10 ⁻⁵
KP10-08	-257.6	-6.2	4.1x10 ⁻⁵
KP10-09	-267.2	-8.8	6.4x10 ⁻⁷
KP10-10	-282.1	-8.8	6.4x10 ⁻⁷

Chemical synthesis of selected peptides

The 10 selected KP10 analogues were synthesised by solid-phase peptide synthesis (SPPS) using standard Fmoc chemistry on Rink amide resin¹³. Coupling was performed with HBTU/HOBt and DIPEA, and peptides were cleaved from the resin with a TFA-based cocktail. Crude products were purified on Sep-Pak C18 cartridges and confirmed by electrospray ionisation mass spectrometry (ESI-MS). Purified peptides were lyophilised and stored at -20 °C until biological testing.

Cytotoxicity and migration assays in cervical cancer cells

The antiproliferative activity of KP10 and its 10 analogues were evaluated in HeLa cells by MTT assay¹⁴ after 48 hours of treatment at 10–500 nM. Most peptides induced a dose-dependent decrease in cell viability. KP10-09 and KP10-10 showed the strongest effects, reducing viability to 1.6% and 7.7% at 500 nM, compared with 74.1% for KP10. KP10-05 also showed high cytotoxicity (23.7% viability) (Figure 1). Some analogues displayed non-linear profiles, suggesting compensatory cellular mechanisms. These results demonstrate that sequence modifications can enhance KP10 cytotoxicity against cervical cancer cells. Calculated IC₅₀ values were 1618 nM for KP10, 0.2466 nM for KP10-09, and 0.5364 nM for KP10-10, confirming their markedly greater potency relative to the native peptide.

To further assess functional activity, KP10-09 and KP10-10 were selected for migration assays based on their strong cytotoxic effects. A wound healing assay at 100 nM evaluated their influence on HeLa cell migration. The mean open wound area was quantified at 0, 24, 48, and 72 hours for untreated controls, KP10, and the analogues (Figure 2). At 24 hours, KP10-09 and KP10-10 maintained larger wound areas (63.37% and 64.01%) than the control (40.29%) and KP10 (55.26%), a trend persisting through 72 hours (18.71% and 14.62% vs. 1.12% for control). Both analogues significantly delayed wound closure compared with native KP10, demonstrating sustained inhibition of cell migration and supporting their potential to limit metastatic progression in cervical cancer.

¹³R. B. Merrifield, "Solid Phase Peptide Synthesis. I. the Synthesis of a Tetrapeptide," *Journal of the American Chemical Society* 85, no. 14 (1963): 2149–54, <https://doi.org/10.1021/ja00897a025>.

¹⁴Tim Mosmann, "Rapid Colorimetric Assay for Cellular Growth and Survival: Application to Proliferation and Cytotoxicity Assays," *Journal of Immunological Methods* 65, no. 1–2 (1983): 55–63, [https://doi.org/10.1016/0022-1759\(83\)90303-4](https://doi.org/10.1016/0022-1759(83)90303-4).

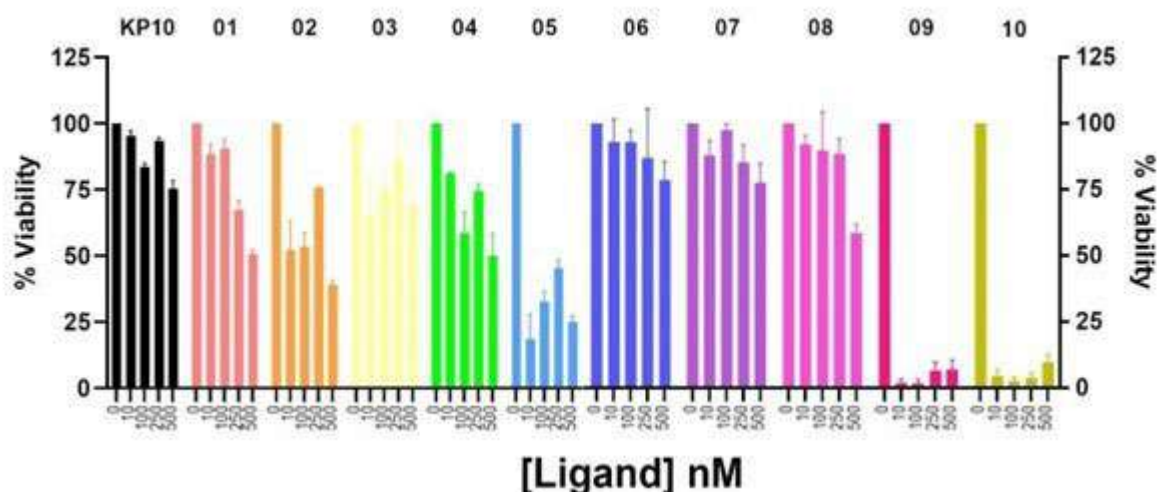


Figure 1: Cell viability of HeLa cells treated with KP10 and its analogues. HeLa cells were treated with increasing concentrations (10, 100, 250, and 500 nM) of KP10 and 10 synthesised analogues for 24 hours. Cell viability was measured using the MTT assay and is expressed as a percentage relative to untreated control cells (set at 100%). Data represent the mean $\pm$ standard deviation of three independent experiments. A dose-dependent reduction in viability was observed for most analogues, with KP10-09 and KP10-10 showing the strongest cytotoxic effects at 500 nM.

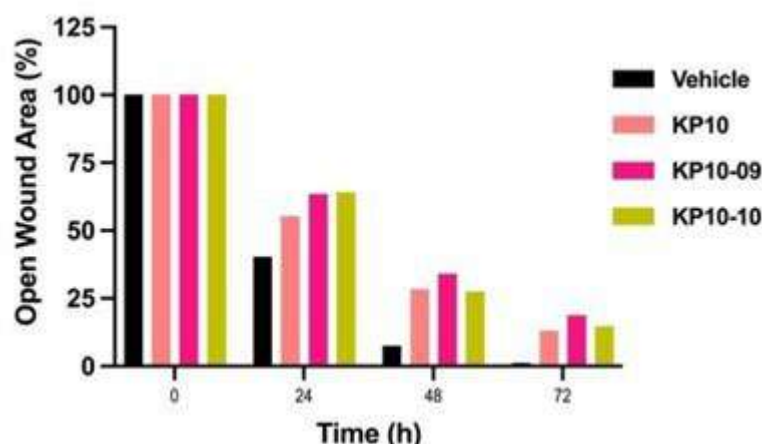


Figure 2: Inhibitory effects of KP10, KP10-09, and KP10-10 on HeLa cell migration assessed by wound healing assay. Cells were treated with 100 nM of each peptide, and the mean percentage of open wound area was measured at 0, 24, 48, and 72 hours for untreated controls, native KP10, and its analogues. Bars represent the average wound area (%) remaining over time, indicating delayed wound closure in cells exposed to the analogues.

Conclusion

This study demonstrates the value of integrating AI-driven peptide design, molecular modelling, and experimental validation to identify KP10 analogues with enhanced antitumour activity. From the computational library, 10 peptides were synthesised and tested *in vitro*; KP10-09 and KP10-10 showed the strongest cytotoxicity and migration inhibition in HeLa cells, consistent with *in silico* predictions. These results highlight the efficiency of computational pipelines for early peptide discovery and support the potential of rationally engineered kisspeptin analogues as leads for cervical cancer therapy.

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Part II
Sustainable and Resilient
Infrastructure

Chapter 13

Co-creating Cities with AI and Digital Twins: A Multispecies Participatory Approach

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Abstract

Urban participatory design has expanded in recent years through digital tools, yet remains largely human-centred, overlooking the needs of non-human stakeholders. This paper presents a methodological framework that integrates ecological signals into participatory processes through a digital twin, enabling multispecies co-creation. The approach was tested in the GreenInCities Barcelona pilot site, where three complementary methods were applied: (i) vegetation analysis using NDVI values applied to drone imagery to assess greenery health, coverage, and typology; (ii) species monitoring through participatory observations and camera traps, generating heat maps of local fauna presence; and (iii) microclimate modelling combining AI simulations and environmental data to map thermal comfort conditions for non-humans. Early results demonstrate how these indicators, when embedded as interactive layers in the digital twin, informed participatory sessions and shaped concrete design strategies, such as bridging vegetation corridors, wildlife refuges, shading interventions, and lighting design adaptations. Beyond enriching co-analysis and co-design, the framework supports co-monitoring by allowing indicators to be updated and revisited over time, creating a feedback loop that sustains multispecies participation throughout the project lifecycle. In doing so, it establishes a replicable and scalable pathway for embedding non-human needs into urban planning and highlights the new role of humans as mediators and allies for other species through technology.

Keywords: *Cross-disciplinary innovations, Cognitive Cities, Urban planning and design, Digital twin, Co-creation*

Introduction

Participatory urban design has evolved significantly, from the community-driven advocacy of Jane Jacobs¹ and Arnstein's "Ladder of Participation"² to today's digitally enhanced processes that use GIS, VR, and AI to expand citizen engagement³. These tools have broadened opportunities for inclusion, yet participation remains largely human-centred: citizens are empowered, but only human citizens. In

¹Jane Jacobs, *The Death and Life of Great American Cities* (New York: Random House, 1961).

²Sherry R. Arnstein, "A Ladder of Citizen Participation," *Journal of the American Institute of Planners* 35, no. 4 (1969): 216–24, <https://doi.org/10.1080/01944366908977225>

³Junjie Luo et al., "Urban Digital twins for Citizen-Centric Planning: A Systematic Review of Built Environment Perception and Public Participation," *International Journal of Applied Earth Observation and Geoinformation* 143 (2025): 104746, <https://doi.org/10.1016/j.jag.2025.104746>

parallel, scholarship on urban ecology highlights the importance of biodiversity and multispecies interactions for resilience⁴. However, non-human life is often framed in utilitarian terms, as providers of ecosystem services, rather than as stakeholders with needs and vulnerabilities. Multispecies theorists such as Haraway⁵ and Tsing⁶, and recent debates in multispecies urbanism and justice⁷, argue for recognising cities as shared habitats shaped by more-than-human collaborations⁸. Despite these contributions, non-humans remain absent and underrepresented in urban participatory processes. At the same time, new digital tools, including GIS, VR, AI, and digital twins, have been introduced to expand participation by making complex data accessible and immersive⁹. These technologies allow non-experts to visualise information and explore scenarios, but they remain focused on human users and lack pathways to incorporate ecological signals into decision-making. This paper addresses that gap by presenting a framework in which ecological indicators, derived from vegetation analysis, wildlife monitoring, and microclimate simulations, are integrated into a digital twin environment. This approach makes the presence and wellbeing of non-human stakeholders visible and debatable within participatory processes. By translating ecological signals into shared design indicators, the framework redefines participatory urban design as a multispecies co-creation, where humans act not only as beneficiaries but also as allies and mediators for non-humans.

Methods for Non-human Participation

Non-human species cannot participate directly in design processes; their signals must be translated into indicators that can represent them in the co-creation process. The proposed methodological framework structures three methods with a data workflow starting from the signal to be collected and ending in its possible participatory use in the participatory phases of co-analysis, co-design, and co-monitoring. In this framework, technology supports signals collection, interpretation, and visualisation to make ecological needs visible and understandable.

This framework was tested in the GreenInCities project¹⁰ Barcelona pilot site, a promenade near the Besòs river mouth. Since September 2024, biodiversity experts, technicians, students, citizens, and policymakers have engaged with this novel approach to co-analyse site conditions and co-design

⁴Marina Alberti, *Cities That Think Like Planets: Complexity, Resilience, and Innovation in Hybrid Ecosystems* (University of Washington Press, 2016).

⁵Donna Haraway, *The Companion Species Manifesto: Dogs, People, and Significant Otherness* (Prickly Paradigm Press, 2003).

⁶Anna L. Tsing, *The Mushroom at the End of the World: On the Possibility of Life in Capitalist Ruins* (Princeton University Press, 2015).

⁷Danielle Celermajor et al., "Multispecies Justice: Theories, Challenges, and a Research Agenda for Environmental Politics," *Environmental Politics* 30, no. 1–2 (2020): 119–40, <https://doi.org/10.1080/09644016.2020.1827608>

⁸Alberti, *Cities That Think Like Planets*, 221–240.

⁹Luo et al., "Urban Digital Twins for Citizen-centric Planning: A Systematic Review of Built Environment Perception and Public Participation," 2025.

¹⁰CORDIS, "GreenInCities," European Commission, December 21, 2023, <https://cordis.europa.eu/project/id/101139730>

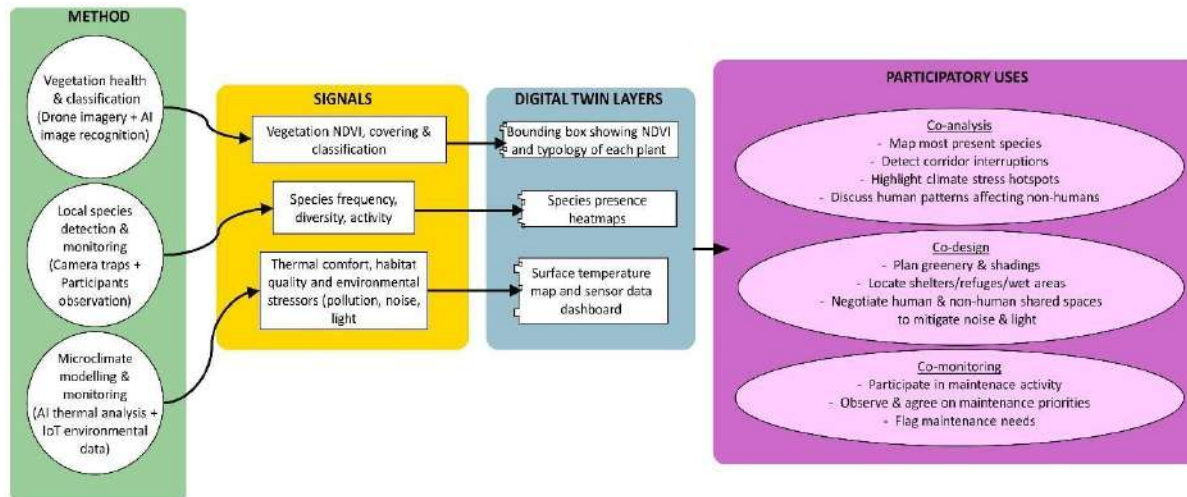


Figure 1: Methodological framework workflow.

interventions. While some sensor deployments remain pending due to administrative permits, digital twin of the site was successfully developed and initial results from vegetation analysis, species monitoring, and thermal modelling have already been integrated into participatory sessions.

Vegetation analysis

Local vegetation presence, health, and diversity affect the habitat conditions of local fauna and inform maintenance needs together with landscape choices. Automated collection of this data is performed through AI-based computer vision and machine learning algorithms that analyse and process drone imagery to classify vegetation by type and to calculate the normalised difference vegetation index (NDVI), a proxy for plant health. The data, when integrated as layers in the digital twin, provide a quantitative picture of vegetation health and presence across the pilot site, making possible to estimate both the condition and percentage coverage of greenery. In GreenInCities, NDVI values and plant typologies were integrated in the digital twin through a bounding box for each vegetation unit, showing NDVI values, ranged between 0.00 (no vegetation) and 100.00 (healthiest vegetation), and vegetation typologies such as trees, shrubs and grass. This information allowed participants to identify where the site was healthy, organise a catalogue of vegetation typology, and detect where ecological functions might be weaker. The representation offered a shared basis for discussion, guiding priorities such as replanting, maintenance, or the design of continuous green corridors to improve connectivity.

Species monitoring

Understanding local fauna presence and habits is important for planners to identify zones that need protection or corridors that support species movement. Datasets are built with analysis results of image detection technique applied on the images collected through camera traps and with participant observations conducted through guided walks with experts and supported by apps such as iNaturalist¹¹. Species frequency, diversity indices, and temporal patterns are obtained and then converted into spatial

¹¹iNaturalist. "iNaturalist," n.d. <https://www.inaturalist.org/>

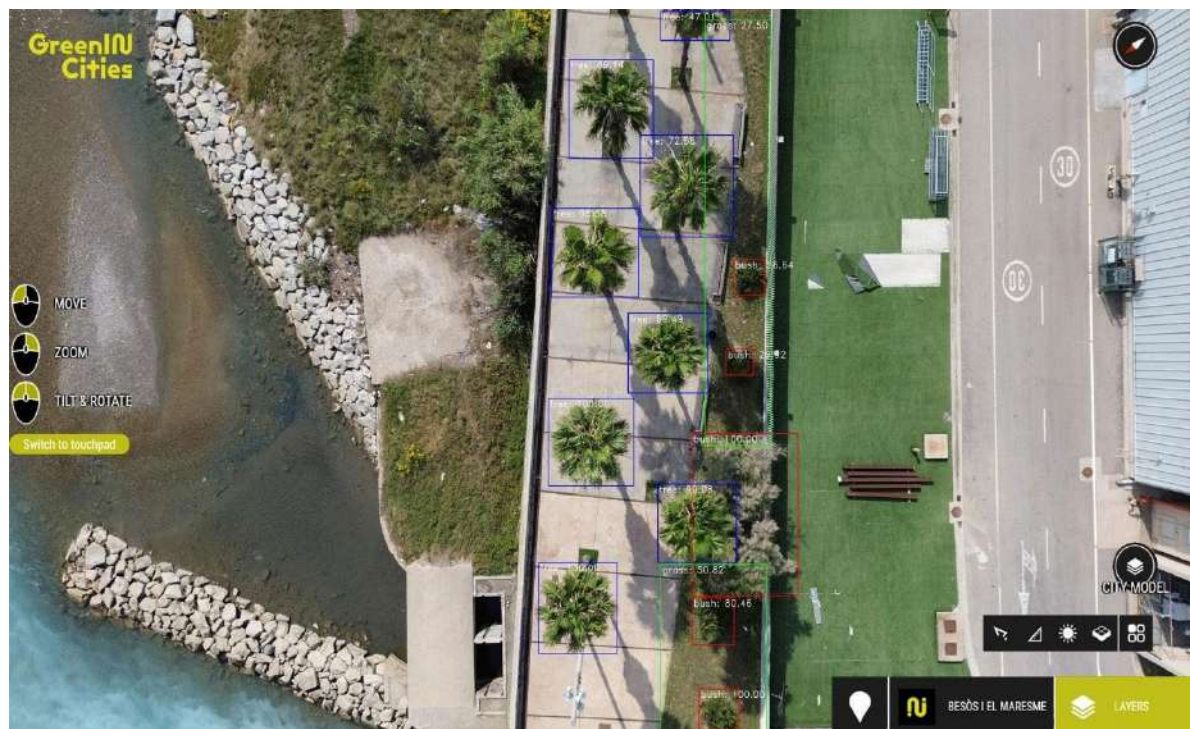


Figure 2: NDVI analysis and vegetation classification map visualised as a Digital twin layer.

heat maps showing areas of higher or lower species use and integrated in the digital twin for visualisation.

In the GreenInCities project, this workflow was applied through direct observation and highlighted the parts of the site most frequented by different species (e.g. near the river for terrestrial species), becoming a practical tool for citizens' engagement. It inspired and informed proposals for aerial species refuges, the definition of new ecological corridors near the river, and the redesign of lighting strategies to minimise disturbance in sensitive areas. Camera traps, expected to be deployed in the next months to expand the temporal and spatial resolution of species data, will add nocturnal and seasonal patterns to the participatory process.

Microclimate modelling

Microclimate conditions, such as temperature and noise levels, influence the comfort of urban areas not only for humans but also for other species. Urban designers can modify these conditions through interventions, for example by selecting specific pavement materials or increasing climate sheltered areas. AI-supported thermal modelling and environmental sensors are used to analyse comfort. Through computer vision and machine learning analysis of drone imagery or render of future scenarios, surface materials are classified and using physics-based AI models their thermal performance under site-specific conditions are estimated. IoT sensors (measuring air temperature, humidity, noise, and light levels) validate these simulations and provides real time data. This information is visualised into the digital twin through colour based thermal maps and dashboard boxes.

In GreenInCities, participants could directly explore which areas were heat-vulnerable and how design interventions might change outcomes. Thermal modelling revealed stark contrasts between surface types under summer conditions. Exposed concrete was simulated to reach up to 45–50 °C, while shaded



Figure 3: Local fauna detection outputs (terrestrial species) from direct observation and use of iNaturalist integrated into the digital twin as heat maps.

concrete stayed closer to 25–30 °C, and vegetated surfaces remained around 20–25 °C. This provided an evidence base for identifying hotspots, testing cooling strategies, and evaluating the implications of design interventions for both human and non-human comfort.

In fact, these variations have immediate ecological implications: for example, pollinators reduce activity above approximately 30–32 °C¹², while amphibians show stress above 35 °C¹³. This led to proposals for tree planting, shading shelters, and permeable materials, with early design simulations already demonstrating measurable improvements in surface temperatures. Future deployment of IoT sensors will validate and enrich these simulations, creating a real-time feedback loop for co-monitoring.

Results

The achieved results from applications of the methodological framework in the Barcelona pilot demonstrate how ecological signals, translated into indicators through technology, can influence urban design decisions that are both scientifically robust and participatory. NDVI analysis highlighted where vegetation is thriving or under pressure, heat maps of observed fauna revealed areas of ecological importance, and thermal modelling demonstrated how surface materials shape multispecies comfort areas. Communicating these results in a shared and interactive format, such as a digital twin, enabled citizens, experts, and policymakers to engage in discussions where non-human needs became visible and were incorporated as relevant design inputs.

¹²Koppert, Plant–Pollinator Interactions in High Temperatures, Glasshouse Consultancy, 2020.

¹³Patrice Pottier et al., “Vulnerability of Amphibians to Global Warming,” *Nature* 639 (2025): 954–61, <https://doi.org/10.1038/s41586-025-08665-0>



Figure 4: Map of surfaces temperature layer integrated within the digital twin as thermal map.

Conclusions

The application of the proposed methodological framework aimed to illustrate the kinds of design outcomes that can be achieved through multispecies co-creation, while also showing how participatory urban planning can become more inclusive with non-humans, ultimately enhancing ecological resilience in future cities and shifting participation from an anthropocentric exercise toward a multispecies negotiation.

An additional strength of this framework lies in its potential for validating design strategies. In fact, by continuous monitoring of ecological indicators after project implementation, the success of urban regeneration projects can be measured and eventual needs for adaptive management can be flagged. In this way, participation does not end with the design phase but continues through implementation and maintenance, keeping non-human needs present throughout the lifecycle of the project.

While further testing and scaling are required, the combined use of AI, digital twins, and participatory practices confirms both the feasibility and the added value of multispecies participation in urban design. By making non-human signals legible, the framework positions citizens not only as beneficiaries but also as allies and mediators for other species, paving the way toward cities that are more just, resilient, and ecologically attuned.

Acknowledgements

This project has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement No. 101079267 (GreenInCities).

We acknowledge the contributions of KTU (digital twin development); Consorci Besòs, MCRIT and PEMB (participatory process); MAA02-2024/2025 students (biodiversity mapping).

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Chapter 14

ThermoChroma-smart Colorimetric Sensors as Cold Chain Indicators

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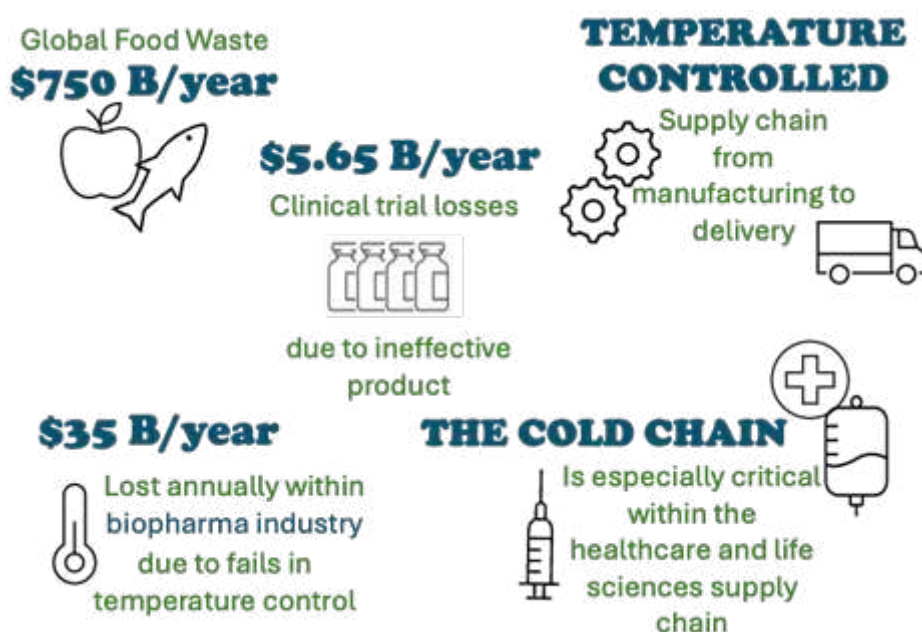
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Abstract

Cold chain failures of pharmaceuticals result in substantial economic and clinical losses. Conventional monitoring systems, like selected batch analysis, in-situ electronic sensors, and time-temperature indicators, provide reliable data but remain costly, infrastructure-dependent, and impractical for per-item implementation. This paper introduces a photonic colorimetric sensor design that provides a simple, visual readout of cold chain integrity. The photonic system exploits the thermoresponsive cholesteric phase of cellulose derivatives, which undergoes distinct and reversible colour shifts from 0°C to room temperature. Preliminary prototypes demonstrate integration into packaging formats, with scalability through solution processing and printing routes and colour response is just within minutes. With a scope to investigate temperatures below 0°C, this approach offers a sustainable, low-cost alternative to electronic monitoring systems and establishes photonic architectures derived from natural resources as promising candidates for cold chain monitoring.

Keywords: *Colorimetric Sensors, Sustainable Development, Structural Colour, Cellulose photonics, Cold chain detection*



Infographic illustrating key industries dependent on cold chain integrity

Introduction

Temperature-controlled logistics, commonly referred to as cold chains, are essential for preserving the efficacy and safety of temperature-sensitive products across diverse sectors, including, life sciences and medical devices as well as perishable and frozen food and industrial chemicals, and reagents, as shown in Figure 1 below¹.

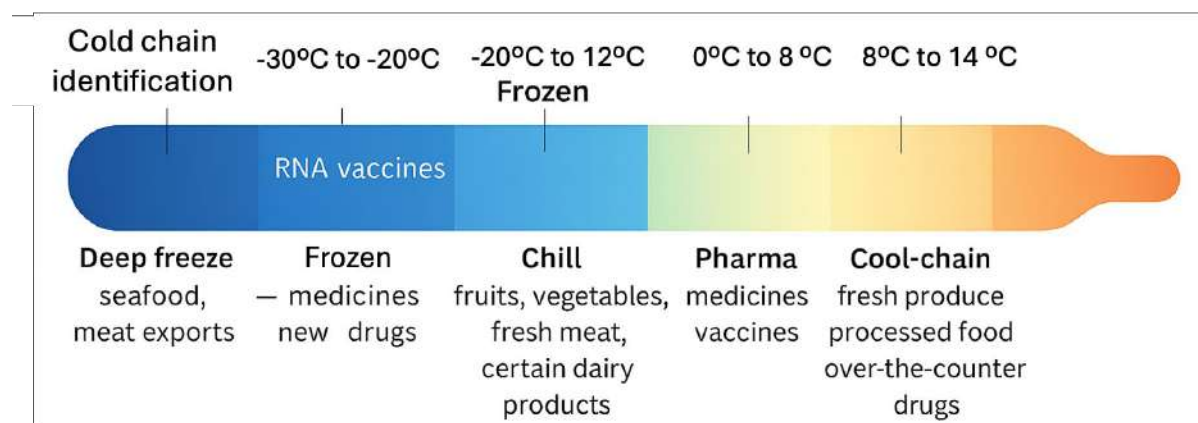


Figure 1: Schematic illustration of critical cold storage zones, highlighting temperature ranges required for the safe handling of temperature-sensitive goods across the cold chain.

One of the most important criteria in terms of sustainability is the shelf-life of a pharmaceutical modality. Temperature variations in transit, warehouse storage management conditions and delays as well as the breakdowns that might constitute moderate inconveniences in a typical supply chain can have devastating impacts for pharmaceutical cold chains crucial for the development of the new drug modalities such as gene and cell therapy relevant biological components, m-RNA drugs, and complex biochemicals. A single anomaly in the cold chain can render entire batches of products unusable, contributing to the alarming statistics mentioned above. The pharmaceutical industry faces staggering losses, with failures in the cold chain alone costing an estimated 29 billion GBP annually². To mitigate these risks and reduce the environmental footprint of the chemical processes involved in pharmaceuticals, there is an urgent need for innovative tools that offer simple and cost-effective monitoring of the cold chain for individual components. Such intervention is expected to make a great impact by reducing wastage and decreasing the use of raw materials.

Existing cold chain monitoring technologies ranging from electronic data loggers and radio frequency identification (RFID)-enabled sensors to time-temperature integrators provide accurate tracking but are limited by cost, infrastructure requirements, and restricted suitability for dose-level deployment. These constraints leave a technological gap for simple, scalable indicators that can be integrated into individual packaging and interpreted without specialist equipment.

Monitoring visual colour changes is a widely used strategy in biological signalling systems. This allows direct interpretable signalling without supplemental tools. To achieve such monitoring capacity,

¹Tempk, "What Is the Cold Chain? 2025 Temperature-controlled Guide," November 14, 2025, <https://www.tempcontrolpack.com/knowledge/what-is-the-cold-chain-2025-temperaturecontrolled-guide/>

²Stefan Lutzmayer, Elina Osoianu, and Tom Rosenfield. Tip of the Iceberg: Economic and Environmental Impact of the Vaccine Cold Chain. IQVIA White Paper. 2025.

pigment-based indicators have been explored, but they often suffer from poor stability, leaching, and limited adaptability across different temperature regimes. By contrast, structurally coloured photonic materials provide robust optical responses arising from periodic nanoscale order, and their spectral properties can be engineered to respond to environmental stimuli.

This paper introduces the design of a photonic colorimetric sensor utilising the cholesteric liquid crystalline phase of cellulose with thermoresponsive block copolymers. Unlike pigments, structural colour arises from the periodic organisation of matter at the nanoscale, producing vivid and highly stable optical responses³ (4). Hydroxypropyl cellulose (HPC), in particular, forms cholesteric liquid crystalline phases that display strong colour changes in response to temperature and humidity^{4–567} (5–8). When combined with block copolymer (BCP) hydrogels, the resulting hybrid material enables tuning of the thermal response, improving sensitivity in narrow temperature ranges and enhancing the processability of cellulose into scalable formats. This system presents tuneable colour changes in the critical 0°C to 8°C range and up to room temperature relevant to pharmaceutical cold chains. The preliminary devices demonstrate rapid, visible, and reversible (or lockable) colour changes and compatibility with scalable processing methods such as thin-film deposition and printing. These results establish polysaccharide-based photonic systems as a promising platform for sustainable and low-cost cold chain monitoring. The hybrid HPC-BCP system responds rapidly, within minutes, and can be engineered for reversible or irreversible behaviour depending on the application. Importantly, the system operates without breaching the package seal, thereby ensuring integrity during storage and transport⁸

Results and Discussion

Inspired by the colour changing biological creatures such as beetles or cuttlefish skin, our photonic sensing design accounts for producing a multi-layered colorimetric smart indicator directly monitoring the cold chain. We coined this design as ThermoChroma, which is a photonic sensor (producing colour through light interference rather than pigments) that translates temperature fluctuations in the pharmaceutical cold chain into a clear colour signal visible to the naked eye. Such response stems from materials intrinsic temperature sensitivity. Unlike pigment-based indicators, which function like litmus

³Ahu Gümrah Dumanli and Thierry Savin, “Recent Advances in the Biomimicry of Structural Colours,” *Chemical Society Reviews* 45, no. 24 (2016): 6698–724, <https://doi.org/10.1039/c6cs00129g>

⁴Tadeusz Balcerowski et al., “Hierarchical Organization of Structurally Colored Cholesteric Phases of Cellulose via 3D Printing,” *Small* 19, no. 8 (2022): e2205506, <https://doi.org/10.1002/smll.202205506>

⁵Hongning Ren, Tadeusz Balcerowski, and Ahu Gümrah Dumanli, “Achieving a Full Color Palette With Thickness, Temperature, and Humidity in Cholesteric Hydroxypropyl Cellulose,” *Frontiers in Photonics* 4 (2023), <https://doi.org/10.3389/fphot.2023.1134807>

⁶Gen Kamita et al., “Biocompatible and Sustainable Optical Strain Sensors for Large-Area Applications,” *Advanced Optical Materials* 4, no. 12 (2016): 1950–54, <https://doi.org/10.1002/adom.201600451>

⁷Gen Kamita, Silvia Vignolini, and Ahu Gümrah Dumanli, “Edible Cellulose-based Colorimetric Timer,” *Nanoscale Horizons* 8, no. 7 (2023): 887–91, <https://doi.org/10.1039/d3nh00006k>

⁸Dumanli and Savin, “Recent Advances in the Biomimicry of Structural Colours,” January 1, 2016.

paper and often lack stability, ThermoChroma relies on structural colour generated by periodic nanoscale order, delivering robust, tuneable, and sustainable performance.

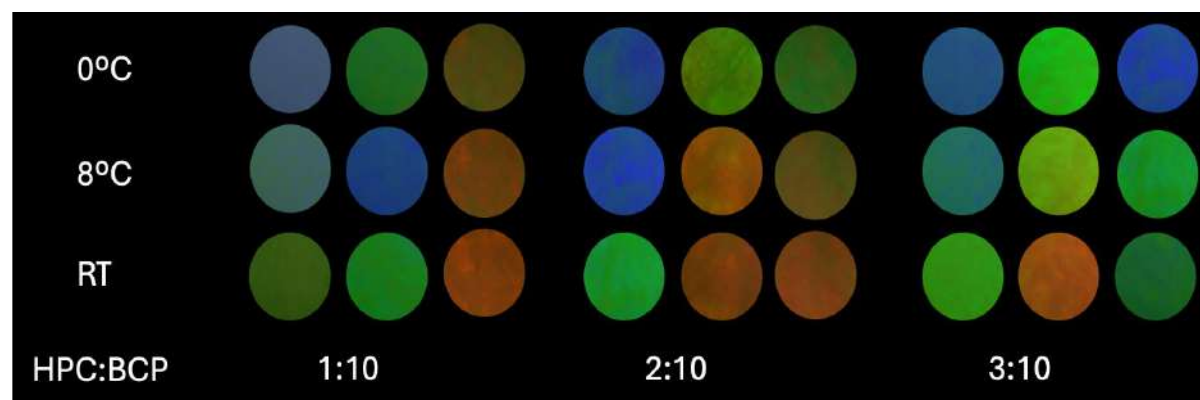


Figure 2: Digital camera images of the ThermoChroma's HCP/BCP sensors, and their colour response to cold simulation test where the temperature was varied between room temperature (RT) and 0°C, showing a distinct and reversible shift in their macroscopic appearance between 0°C and RT.

At the core of the device is HPC, a renewable polysaccharide that naturally forms cholesteric liquid crystalline phases. These phases produce vivid, angle-dependent colours that shift in response to external stimuli, in this case temperature. To enhance the sensitivity and tunability of this platform, we incorporated a block copolymer (BCP) hydrogel that modulates the thermal response. Specifically, temperature responsive block copolymer BCP, poly(glycerol monomethacrylate)-*b*-poly(2-hydroxypropyl methacrylate) (PGMA-*b*-PHPMA) was used in this work to acts as a responsive scaffold, adjusting the phase transition properties of the HPC system and amplifying subtle temperature changes into sharper optical shifts⁹ (9). Figure 2 demonstrates HPC-based sensors with distinct and reversible transition in colour between 0°C and room temperature, marking the critical threshold for pharmaceutical cold chain integrity (6).

Photonic HPC-BCP constructs in the film form were prepared by casting HPC-BCP solutions with varying concentrations of HPC in water from 55% to 64% with a HPC to BCP ratio 10:1, 10:2, and 10:3. The film thickness of the colorimetric indicators were adjusted to 0.5 mm to 1 mm. The films were sealed in semipermeable membranes and the HPC-BCP composites were kept as hydrogels to allow dynamic colour responses. The HPC-BCP solutions were self-assembled to form a mesophase with cholesteric ordering (Figure 3). The reflection wavelength of the cholesteric hybrid system can be described by the modified Bragg equation^{10, 11, 12}:

$$\lambda = n p \cos \cos \theta \quad (\text{Equation 1})$$

and

⁹Qi Yue et al., "Multifunctional Self-Assembled Block Copolymer/Iron Oxide Nanocomposite Hydrogels Formed from Wormlike Micelles," *ACS Applied Materials & Interfaces* 16, no. 16 (2024): 21197–209, <https://doi.org/10.1021/acsami.4c03007>

¹⁰Kamita, Vignolini, and Dumanli, "Edible Cellulose-Based Colorimetric Timer," January 1, 2023.

¹¹Hl. De Vries, "Rotatory Power and Other Optical Properties of Certain Liquid Crystals," *Acta Crystallographica* 4, no. 3 (1951): 219–26, <https://doi.org/10.1107/s0365110x51000751>

¹²Ahu Gümrah Dumanli et al., "Digital Color in Cellulose Nanocrystal Films," *ACS Applied Materials & Interfaces* 6, no. 15 (July 9, 2014): 12302–6, <https://doi.org/10.1021/am501995e>

$$n_{av} = n_{HPC-BCP} \phi_{HPC-BCP} + n_{Water} \phi_{Water} \quad (\text{Equation 2})$$

where n is the average refractive index, and p is the cholesteric pitch (where the consecutive pseudo layers undergo a 360° rotation of the cholesteric structure), ϕ is the volume fraction and θ is the angle of incidence of light with respect to the normal. The refractive index of the hybrid system is considered as $n_{HPC-BCP} = 1.5$.

To demonstrate potential integration into pharmaceutical contexts, our proof-of-concept prototype set up for the ThermoChroma films were sealed to emulate packaging and subjected to controlled cold-chain cycling between 0°C and 20°C . Distinct, visible colour transitions were observed under ambient lighting, readily captured with a smartphone camera (Figure 2). This preliminary validation highlights the applicability of ThermoChroma sensors in real-world logistics environments. Microstructural analysis of the films using cross sectional imaging with scanning electron microscope (SEM) revealed that near perfect helicoidal ordering characteristic of cholesteric photonic systems (Figure 3a), closely resembling the layered cuticle of scarab beetles (Figure 3b). This ordered architecture underpins the distinct spectral shift observed in reflectance measurements, with λ_{max} moving from orange (~ 600 nm) towards greenish blue (~ 450 nm) across the 0°C to 20°C range (Figure 3c). The response can be engineered to be reversible, resetting with temperature, or irreversible, locking into a distinct colour once a threshold is breached. The latter provides a powerful tool for quality assurance: a single glance can confirm whether a medicine has been compromised.

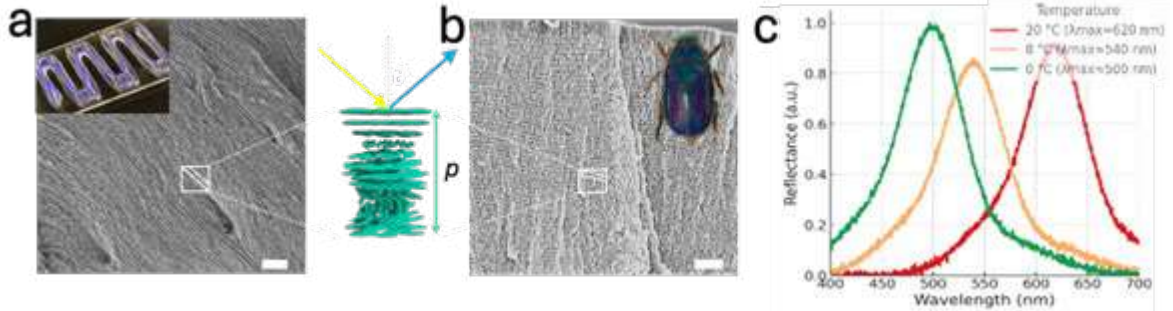


Figure 3: SEM micrographs of the a. HPC/BCP films reveal the cholesteric pitch (p) and periodic ordering responsible for structural colour and b. The cholesteric structure found in *Anoplognathus smaragdinus* beetle cuticle. Scale bars 1 micron. c. The reflectance analysis of the ThermoChroma sensor's colour response, showing a distinct and reversible shift in hue between 0°C and room temperature.

Beyond single-point readouts, the ThermoChroma platforms can be patterned into films, codes, or tags, using scalable methods such as 3D printing or roll-to-roll coating. This opens opportunities for integration into pharmaceutical packaging, food logistics, and even QR-like codes for digital verification. The technology provides not just a functional sensor but a pathway towards sustainable, low-cost, and item-level monitoring of cold chains, with the potential to substantially reduce waste and carbon footprints across supply networks.

Conclusion

ThermoChroma prototypes address key limitations in current cold chain monitoring by combining the cholesteric liquid crystalline HPC hybrids with self-assembled block copolymer BCP hydrogels to

provide visible signal of temperature changes. The existing prototypes demonstrate optical responses across the critical 0–8 °C range and up to room temperature, directly relevant to pharmaceutical storage. The devices exhibit fast, distinct, and reversible colour changes that can also be engineered into irreversible “lock-in” responses once a threshold is crossed, ensuring permanent visual confirmation of cold-chain breaches. Beyond simple visible readouts, ThermoChroma also enables the creation of advanced security features, such as 3D-printed codes or patterned indicators, adding a new layer of traceability and protection against tampering or counterfeiting. Importantly, the platform can be extended to lower-temperature regimes, including the –20 °C storage required for next-generation vaccines, complex pharmaceuticals, and mRNA therapeutics.

Acknowledgements

The authors would like to acknowledge the following funding sources: Royal Society Research Grant [RGS/R2/202434] and BP-ICAM Kathleen Lonsdale Research Fellowship and Henry Royce Institute for Advanced Materials, funded through EPSRC grants [EP/R00661X/1, EP/S019367/1, EP/P025021/1 and EP/P025498/1].

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Chapter 15

Reengineering Ancient Materials for Durable, Low-carbon Structures

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Abstract

Ancient structures exemplify sustainable construction by utilising locally available and recycled materials such as lime, sand, brick dust, charcoal, legume flour, and small aggregates in their binders. Beyond lime and sand, these components are primarily waste products, brick powder acts as a pozzolan, charcoal enhances workability, and legume flour improves shrinkage resistance, cohesion, and flexural strength. Such eco-friendly mixtures have ensured durability for centuries, outlasting modern cementitious systems. This study focuses on Ramkot Fort, a 900-year-old structure built in 1186 by Sultan Ghayas-Ud-Din, which remains intact despite severe environmental stresses including earthquakes, weathering, and thermal shocks induced by climate change. Detailed analysis of the original mortar revealed a lightweight, breathable composition with low strength but high resilience. A compatible repair mortar was formulated using hydrated lime, local clay, sand, crushed brick, and optimised with polypropylene (PP) fibres to mitigate shrinkage cracks observed under high ambient temperatures ($\sim 45^{\circ}\text{C}$). The new mix achieved enhanced mechanical properties (compressive strength of 1.27 MPa, flexural strength of 1.32 MPa, bond strength of 3.51 MPa) while maintaining breathability and thermal stability. This research proposes a prototype mortar, merging ancient practices with modern improvements, offering a climate-resilient, sustainable, and durable solution for heritage conservation and future eco-friendly construction.

Keywords: *Traditional materials, Modern techniques, Sustainable mortars, Heritage conservation, Climate resilience.*

Introduction

The survival of ancient structures for centuries stands as a testament to the wisdom of traditional construction practices. These structures, built without modern cement, utilised locally available materials such as lime, sand, crushed bricks, charcoal, and organic additives like legume flour, black gram, among others. Such materials, often derived from natural or waste resources, provided durability, breathability, and compatibility with the surrounding environment. In contrast, modern cement-based systems, while offering rapid strength gain, have shown limitations in longevity, especially under harsh climatic conditions. With growing concerns about the environmental impact of cement production and the need to conserve heritage sites, there is increasing interest in revisiting ancient material formulations. This study discusses the integration of traditional materials with modern reinforcement

techniques to develop sustainable, durable, and climate-resilient repair mortars for the conservation of historic masonry structures as well as for future low-carbon construction.

To establish a foundation for this approach, a review of previous research on ancient mortar compositions, natural admixtures, and modern strengthening interventions is necessary. The following section summarises key findings from the literature, highlighting successful examples and research gaps relevant to heritage mortar repair.

Fort et al. (2023) studied the ancient Roman villas of Żejtun in Malta¹. The ancient mortar was prepared using local materials: hydrated lime, reactive aggregates (ceramic and rock fragments), and additive (ceramic powder). The combination of aerial lime with reactive aggregates such as volcanic ash (pozzolana) resulting in a material with hydraulic properties, is considered a remarkable technological achievement of the ancient Romans. This centuries-old approach holds significant relevance for a sustainable future, as it demonstrates how durable construction materials can be developed using low-energy lime binders and locally sourced industrial by-products or natural pozzolans. By minimising dependence on energy-intensive Portland cement and encouraging the use of locally available reactive materials, this technique offers a pathway to reduce carbon emissions, conserve natural resources, and promote environmentally responsible construction practices. Manoharan and Umarani (2022) analysed the ancient temples of Tamil Nadu in India². The results revealed the presence of calcite, silica, and amides. While the first two indicate hydrated lime and sand, the last one indicates the presence of organic proteins. Regional plants rich in carbohydrates, proteins, and fats were traditionally incorporated into lime mortar mixtures, serving as multifunctional additives for enhancing workability, cohesion, and long-term durability of the mortar matrix³. Pradeep et al. (2022) have indicated that the addition of fermented plants enhanced the carbonation of limes and strength⁴. Tsoupra et al. (2022) analysed lime mortars from heritage structures in Kathmandu Nepal⁵. FTIR and chemical tests confirmed the use of organic additives, including black lentil (black gram). The presence of black lentil suggests its historical use to enhance mortar properties. Although exact fermentation recipes are not provided, the study confirms the addition of lentil-derived organics, likely in paste or water form.

The present study focuses on the development of mortar specimens composed of hydrated lime, sand, brick particles and powder, and polypropylene (PP) fibres. The specimens were evaluated for key physical and mechanical properties. This research aims to formulate a contemporary lime-based mortar

¹R. Fort et al., "The Technology of Ancient Lime Mortars from the Żejtun Roman Villa (Malta)," *Archaeological and Anthropological Sciences* 15, no. 15 (2023), <https://doi.org/10.1007/s12520-022-01710-3>.

²Abirami Manoharan and C. Umarani, "Lime Mortar, a Boon to the Environment: Characterization Case Study and Overview," *Sustainability* 14, no. 11 (2022): 6481, <https://doi.org/10.3390/su14116481>.

³S. Thirumalini et al., "Knowing from the Past – Ingredients and Technology of Ancient Mortar Used in Vadakumnathan Temple, Tirussur, Kerala, India," *Journal of Building Engineering* 4 (2015): 101–12, <https://doi.org/10.1016/j.jobbe.2015.09.004>.

⁴Saridhe Sriram Pradeep, Sathyanarayana N. Gummadi, and Thirumalini Selvaraj, "Living Mortars-simulation Study on Organic Lime Mortar Used in Heritage Structures," *The European Physical Journal Plus* 137, no. 499 (2022), <https://doi.org/10.1140/epjp/s13360-022-02635-5>.

⁵Anna Tsoupra et al., "A Multi-Analytical Characterization of Mortars from Kathmandu (Nepal) Historical Monuments," *Separations* 9, no. 8 (2022): 205, <https://doi.org/10.3390/separations9080205>.

suitable for the rehabilitation of architectural heritage sites, while also promoting sustainable construction practices inspired by traditional building techniques.

Materials and Methods

Original mortar samples extracted from Ramkot Fort were subjected to general characterisation using modern ASTM and RILEM protocols. Physical properties (density and porosity), chemical composition, and particle size distribution were determined to identify the binder and aggregate fractions. A compact methods table listing test standards, specimen dimensions, curing regime, age at test, and loading rate is given in the form of Table 1. Based on these analyses, the constituent materials and their unit proportions were established. The mortar specimens were accordingly prepared and compared with the modern-day cement sand mortar. For this purpose, a reference cement mortar representative of contemporary masonry practice was prepared with a mix ratio of 1:4 (cement to sand by volume) and a water-to-cement ratio of 0.6. The specimens were prepared and water-cured in accordance with ASTM C109 method⁶. The characteristics were determined after a curing period of 28 days.

Table 1: Summary of experimental methods and test parameters.

Property	Standard	Specimen dimensions	Curing regime	Age (days)	Loading rate/condition
Density and porosity (lime/cement)	ASTM C642–21 ⁷	50 × 50 × 50 mm cubes	Moist-cured 27 ± 2°C/ Oven-dried at 105°C, then water-immersed	28	—
Chemical composition (XRD / XRF)	ASTM C1365-18 ⁸ /ASTM C114–24 ⁹	Powdered samples (<75 µm)	—	—	—
Particle size distribution	ASTM D6913-04(2009)e-1-17 ¹⁰	—	Oven-dried before sieving	—	Mechanical shaker (10 min)

⁶ASTM C109/C109M-20, “Test Method for Compressive Strength of Hydraulic Cement Mortars (Using 2-in. or [50-Mm] Cube Specimens)” (West Conshohocken, PA, 19428-2959 USA: ASTM International, January 15, 2020), https://doi.org/https://doi.org/10.1520/C0109_C0109M-20.

⁷ASTM C642-21, “Test Method for Density, Absorption, and Voids in Hardened Concrete” (West Conshohocken, PA, 19428-2959 USA: ASTM International, December 15, 2021), <https://doi.org/10.1520/C0642-21>.

⁸ASTM C1365-18, “Test Method for Determination of the Proportion of Phases in Portland Cement and Portland-Cement Clinker Using X-Ray Powder Diffraction Analysis” (West Conshohocken, PA, 19428-2959 USA: ASTM International, March 1, 2018), <https://doi.org/10.1520/C1365-18>.

⁹ASTM C114-24, “Test Methods for Chemical Analysis of Hydraulic Cement” (West Conshohocken, PA, 19428-2959 USA: ASTM International, June 1, 2024), <https://doi.org/10.1520/C0114-24>.

¹⁰ASTM D6913-04(2009)e1, “Standard Test Methods for Particle-Size Distribution (Gradation) of Soils Using Sieve Analysis,” in *Book of Standards Volume: 04.09* (West Conshohocken, PA, USA: American Society for Testing and Materials, 2017), <https://doi.org/10.1520/D6913-04R09E01>.

Table 1: Continued.

Property	Standard	Specimen dimensions	Curing regime	Age (days)	Loading rate/condition
Reference cement mortar preparation	ASTM C109–20 ¹¹	1:4, cubes 50 mm.	Water-cured at 27 ± 2 °C	28	—
Bond strength test	RILEM LUM B1 (Modified) ¹²	Brick–mortar–brick prisms	Water-cured at 27 ± 2 °C	28	0.05 MPa/s



Figure 1: Ingredients, composition, and casting of prototypes.

Results and Discussion

Prototype specimens as well as contemporary cement sand mortar samples were tested in terms of flow, density, appearance, and mechanical strength and the results are summarized in Figure 2 and Figure 3. The lime mortar, composed of lime, sand, clay, and brick particles, demonstrated a lower density (1.8 vs. 2.1 g/cm³) and higher flow (150 vs. 100 mm) than cement mortar at equal water content. Despite its lightweight nature, the lime mortar attained a bond strength (3.51 MPa) comparable to cement mortar (3.98 MPa). It should also be noted that lime mortars gain strength slowly compared to their cement counterpart. The higher flow can be attributed to lime, the fine brick, and clay particles, which enhance lubrication within the mix, while the reduced density reflects its porous and breathable structure, beneficial for moisture regulation in historic masonry. The incorporation of PP fibres further improved crack resistance under elevated temperatures (~ 45 °C), ensuring better dimensional stability in hot

¹¹ASTM C109/C109M-20, “Test Method for Compressive Strength of Hydraulic Cement Mortars (Using 2-in. or [50-Mm] Cube Specimens).”

¹²Compendium comp012, “RILEM Recommendations for the Testing and Use of Constructions Materials” (RILEM 14-20 Boulevard Newton, Bâtiment Bienvenue - Cité Descartes, 77420 Champs-sur-Marn, 1994).

climates. Beyond thermal and mechanical performance, the brick particles impart a distinctive pink colour, ensuring better visual integration with heritage structures. The statistical summary of the materials is presented in Table 2. All quantitative tests were conducted in triplicate ($n = 3$), and mean values along with standard deviations are reported. Given the limited number of replicates, the results should be interpreted as indicative trends rather than statistically validated population parameters.

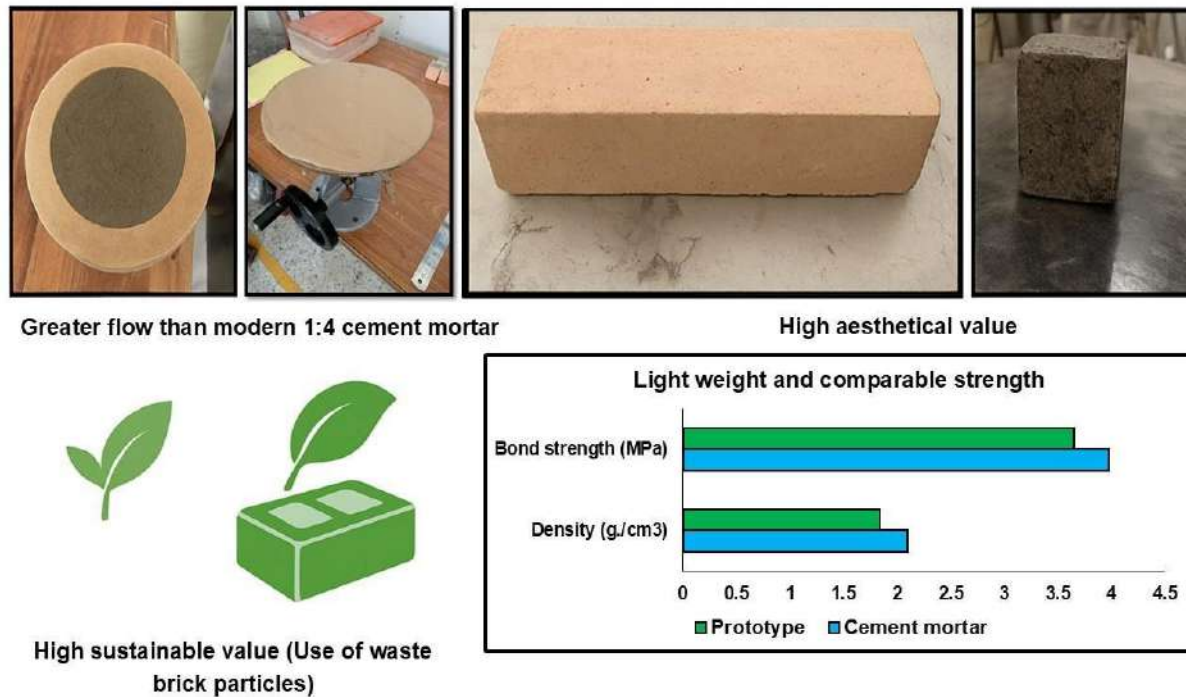


Figure 2: Comparison between lime-brick powder with modern day cement mortar in terms of flow, aesthetics, sustainability, weight, and strength.

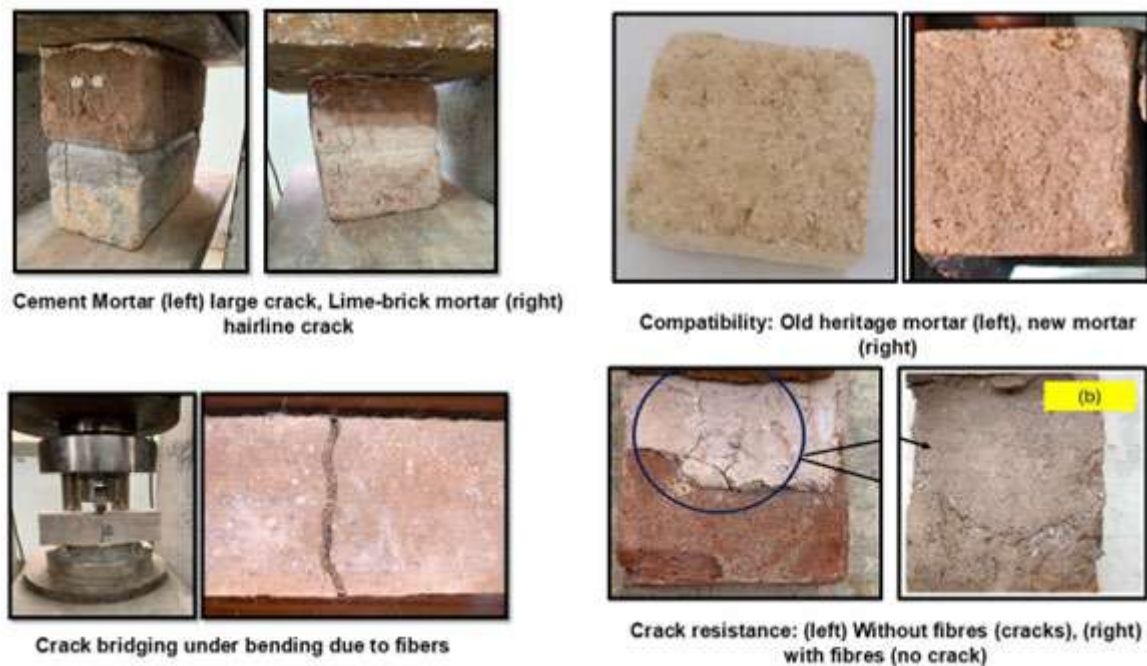


Figure 3: Comparison between lime-brick powder with modern day cement mortar in terms of crack resistance at high ambient temperature (~45°C).

Table 2: Summary of physical and mechanical properties of the investigated mortars (mean $\pm$ standard deviation, $n = 3$).

Specimen	Density (g/cm ³)	Porosity (%)	Bond strength (MPa)	Flexural strength (MPa)
Cement mortar	2.03 $\pm$ 0.03	11.80 $\pm$ 0.36	3.98 $\pm$ 0.06	2.69 $\pm$ 0.07
Heritage-replicated mortar	1.83 $\pm$ 0.02	29.76 $\pm$ 0.86	3.51 $\pm$ 0.04	1.29 $\pm$ 0.06

In this study, the lime–PP mortar performed comparably to the reference cement mortar while offering added benefits of breathability, ductility, and improved compatibility with historic masonry. The use of local clays and recycled brick waste enhance sustainability, whilst the incorporation of PP fibres may prove beneficial in earthquake-prone regions owing to their energy-absorbing capacity. These outcomes, together with previous findings in the literature highlighting the advantages of lime-based mortars over cement mortars in heritage contexts, suggest that the proposed lime–PP system represents a climate-resilient, sustainable, and heritage-compatible alternative for conservation and environmentally friendly construction.

Although a full life-cycle analysis is beyond the current scope, published emission factors indicate that producing Portland cement emits about 0.82–0.90 kg CO₂ per kg of cement¹³, whereas producing quicklime via calcination carries emissions of about 0.8 kg CO₂ per kg (calcination only)¹⁴. Considering that lime mortars often require less processing temperature (around 900 °C compared to ~1450 °C for Portland cement), use fewer high-emission energy inputs, and allow for considerable CO₂ re-absorption during carbonation, the net embodied carbon of lime-based mortars can be substantially lower than that of cement mortars.

Conclusions

The lime mortar formulated with sand, clay, brick particles, and PP fibres proved to be lightweight, workable, and mechanically comparable to cement mortar, whilst offering superior breathability and reduced cracking under thermal stress. Its aesthetic compatibility, cost-effectiveness, and reliance on locally available recycled materials further add to its value. Taken together, these characteristics, along with indications from the literature, suggest that the lime–PP system is a climate-resilient and heritage-compatible option for conservation and environmentally friendly construction.

The findings of this study establish a laboratory-scale foundation for developing durable and low-carbon lime-based mortars. However, their scalability and field performance require further validation. Future work should focus on pilot-scale production and field trials under varying climatic and substrate conditions to assess long-term durability, mechanical stability, and compatibility with existing heritage

¹³Angham Ali Mohammed et al., “Calcium-based Binders in Concrete or Soil Stabilization: Challenges, Problems, and Calcined Clay as Partial Replacement to Produce Low-carbon Cement,” *Materials* 16, no. 5 (2023): 2020, <https://doi.org/10.3390/ma16052020>.

¹⁴Longfei Bing et al., “An Investigation of the Global Uptake of CO₂ by Lime from 1930 to 2020,” *Earth System Science Data* 15, no. 6 (2023): 2431–44, <https://doi.org/10.5194/essd-15-2431-2023>.

materials. Limitations of the present study include the restricted number of mix compositions and controlled curing conditions, which may not fully replicate on-site variability. Extending this work toward standardised mix design protocols and regional raw material optimisation will enable broader practical implementation in sustainable and heritage construction.

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Chapter 16

Designing and Verifying Computational Models for Human-agent Teamwork in Future Cities

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Abstract

We propose a verified human-agent teamwork model for time-critical urban disasters that coordinates humans, drones, and rescue robots while preventing unsafe or unfair behaviours. The model represents heterogeneous capabilities and constraints, allocates tasks via a utility-driven, mixed-initiative negotiation protocol (with human override and justification), and embeds pre-execution formal verification. Candidate joint plans are compiled to petri nets and checked for safety, liveness, fairness, and deadlock-freedom before enactment. We implement the approach by extending the RoboCup Rescue Simulator with drone and rescue-robot agents and evaluate earthquake and urban-fire scenarios on the Kobe and San Francisco maps. Compared to manual coordination, the verified collective accelerates victim detection, reduces responder exposure, and increases evacuation throughput, while the verification step eliminates starvation patterns and highlights design bottlenecks early. Results also show that urban form (road density and fragmentation) materially affects clearance rates, motivating adaptive reprioritisation during operations. Overall, the study demonstrates that integrating formal verification with explainable, mixed-initiative coordination yields robust, transparent human-agent teams for safety-critical city response.

Keywords: *Resilient Infrastructure, Human-agent Teamwork, Disaster Simulation, RoboCup Rescue, Autonomous Systems*

Introduction

Climate-amplified disasters increasingly overwhelm urban incident command, stretching infrastructure and first responders beyond manual coordination's limits in large-scale events¹. In parallel, IoT-enabled drones and ground robots offer real-time sensing, corridor clearance, and logistical support, acting as force multipliers when effectively integrated². Real integration, however, requires agents that not only perceive but also negotiate and coordinate with human operators using principled teamwork behaviours^{3,4}.

¹Nathan Schurr et al. "The Future of Disaster Response: Humans Working with Multiagent Teams Using DEFACTO," In *AI Technologies for Homeland Security: Papers from the 2005 AAAI Spring Symposium*, 9–16, 2005.

²Sarvapali D. Ramchurn et al. "A Disaster Response System Based on Human-Agent Collectives," *Journal of Artificial Intelligence Research* 57 (2016): 661–708, <https://doi.org/10.1613/jair.5098>

³Xiacong Fan and John Yen, "Modeling and Simulating Human Teamwork Behaviors Using Intelligent Agents," *Physics of Life Reviews* 1, no. 3 (2004): 173–201, <https://doi.org/10.1016/j.plrev.2004.10.001>

⁴Schurr et al. "The Future of Disaster Response: Humans Working with Multiagent Teams Using DEFACTO."

We address this need with a resilient human–agent coordination framework that emphasises robustness under uncertainty, transparency, and pre-execution verification. Our approach implements a computational teamwork model in the RoboCup Rescue Simulator and extends it with two agent classes, i.e., rescue robots and drones, to support earthquake and urban fire evacuations^{5,6}.

Related-work

Human–agent teamwork has matured over decades in disaster response, evacuation, and urban resilience, moving from knowledge-sharing and task-allocation frameworks to mixed-initiative teams that negotiate and adapt under shifting priorities^{7–9}. Early work showed that modelling teamwork behaviours, such as communication, cross-monitoring, and adaptive allocation, is critical for realistic large-scale simulations, while later systems added negotiation to reassign tasks as resources and risks evolved^{10,11}.

Several simulators support this research. NetLogo captures emergent crowd dynamics but lacks detailed infrastructure damage models, whereas SUMO offers fine-grained traffic and road-network fidelity without integrated civilians, buildings, or hazards. By contrast, RoboCup Rescue couples civilians, infrastructure, hazard spread, and communications, making it well suited for end-to-end disaster-response studies¹².

Trust and accountability are equally vital as in safety-critical settings, responders must understand and contest autonomous recommendations. Prior approaches, like rule-based reasoning, natural-language rationales, and game-theoretic transparency, often trade interpretability for speed. We address this by building formal guarantees of safety and fairness into the teamwork core, complementing mixed initiative coordination^{13,14}.

For modelling and verification, petri nets concisely capture concurrent human–agent interactions and enable formal analysis of reachability, deadlock-freedom, and liveness. Toolchains such as Snoopy (for visual-design) and Charlie (for automated-analysis) operationalise these checks yet have rarely been applied to disaster-response simulation, an application gap our work begins to close^{15,16}.

⁵Ramchurn et al. “A Disaster Response System Based on Human–Agent Collectives.”

⁶Cameron Skinner and Sarvapali D. Ramchurn, “The RoboCup Rescue Simulation Platform,” In *Proceedings of the 9th International Conference on Autonomous Agents and Multiagent Systems (AAMAS 2010)*, 1647–48, 2010.

⁷Fan and Yen, “Modeling and Simulating Human Teamwork Behaviors Using Intelligent Agents.”

⁸Ramchurn et al. “A Disaster Response System Based on Human–Agent Collectives.”

⁹Schurr et al. “The Future of Disaster Response: Humans Working with Multiagent Teams Using DEFACTO.”

¹⁰Fan and Yen, “Modeling and Simulating Human Teamwork Behaviors Using Intelligent Agents.”

¹¹Schurr et al. “The Future of Disaster Response: Humans Working with Multiagent Teams Using DEFACTO.”

¹²Skinner and Ramchurn, “The RoboCup Rescue Simulation Platform.”

¹³Panagiotis Kouvaros et al. “Formal Verification of Open Multi-agent Systems,” In *Proceedings of the 18th International Conference on Autonomous Agents and Multiagent Systems (AAMAS 2019)*, 179–187, 2019.

¹⁴Ramchurn et al. “A Disaster Response System Based on Human–Agent Collectives.”

¹⁵Monika Heiner et al. “Snoopy – A Unifying Petri Net Tool,” In *Lecture Notes in Computer Science*, 398–407, 2012, https://doi.org/10.1007/978-3-642-31131-4_22

¹⁶Monika Heiner, Schwarick Martin, and Jan-Thierry Wegener, “Charlie – An Extensible Petri Net Analysis Tool,” In *Lecture Notes in Computer Science*, 200–11, 2015, https://doi.org/10.1007/978-3-319-19488-2_10

Model-design

The proposed model integrates three interdependent layers:

1. Representation-layer models the urban disaster environment with geo-referenced maps, building structures, traffic networks, and civilian populations. Agents are described with capability profiles (e.g., drones can fly and perceive heat-signatures, robots can clear debris).
2. Coordination-mechanism uses iterative, and utility-driven negotiation. Agents generate local utility functions based on task priorities. A distributed game-theoretic negotiation protocol reconciles conflicts between agents, ensuring efficient task allocation.
3. Verification-layer: each joint plan undergoes automatic model checking. Properties verified include safety, liveness, and fairness. Embedding verification ensures unsafe or biased plans are never executed.

Simulator Extension

Our study extended the RoboCup Rescue Simulation Server by implementing two novel agent classes:

- Rescue Robot, which was designed to remove debris and create pathways for civilians. Their mobility is governed by a new pathfinding-algorithm capable of navigating dynamic blockades.
- Drone, which provides aerial reconnaissance, scanning buildings for trapped civilians. Once civilians are detected, drones broadcast coordinates to the police officer. Flight path optimisation balances coverage and energy constraints.

The following code snippets illustrates the core implementation for the Rescue Robot (Figure 1 and Figure 2) and Drones (Figure 3 and Figure 4), respectively.

```

1  package sampleagent;
2
3  import
4
5
6
7
8
9  public class SampleRescueRobot extends AbstractSampleAgent<RescueRobot> {
10     private static final Logger LOG = Logger.getLogger(SampleRescueRobot.class);
11     private static final String DISTANCE_KEY = "clear-repair-distance";
12
13     private int distance;
14     private Point2D targetCoordinates;
15
16     @Override
17     public String toString() {
18         return "Sample Rescue Robot";
19     }
20
21     @Override
22     protected void postConnect() {
23         super.postConnect();
24         model.addClass(StandardEntityURN.ROAD, StandardEntityURN.DRONE, StandardEntityURN.RESCUE_ROBOT);
25         distance = (int) Math.round(config.getIntValue(DISTANCE_KEY) * 0.97);
26     }
27
28     @Override
29     protected void think(int time, ChangeSet changed, Collection<Command> heard) {
30         if (time == config.getIntValue(kernel.KernelConstants.ZENDRE_AGENT_COMMANDS_KEY)) {
31             //Subscribe to channel 3
32             sendSubscribe(time, channel.1);
33         }
34         for (Command next : heard) {
35             LOG.info("Heard" + next);
36             if (next instanceof AKSpeak) {
37                 AKSpeak tell = (AKSpeak) next;
38                 String message = new String(tell.getContent());
39                 if (message.startsWith("coordinates")) {
40                     try {
41                         handleGoCommand(message);
42                         LOG.info("Going to coordinates");
43                     } catch (NumberFormatException e) {
44                         LOG.error("Failed to parse coordinates: ", e);
45                     }
46                 }
47             }
48         }
49         if (targetCoordinates != null) {
50             moveToTarget(time);
51         }
52     }
53 }

```

Figure 1: Code snippet for the Rescue Robot agent class.

```

1 private void handleCommand(String message) { //usage: @Leongw994
2     String[] parts = message.split(" ");
3     LOG.info("message length: " + parts.length + " " + message);
4     if (parts.length == 3) {
5         int x = Integer.parseInt(parts[1]);
6         int y = Integer.parseInt(parts[2]);
7         targetCoordinates = new Point2D(x, y);
8         LOG.info("Received coordinates of civilians at: " + x + ", " + y + " free police centre");
9         LOG.info("Received coordinates of civilians at: " + x + ", " + y + " free the drone");
10    }
11 }

12
13 private void moveInTarget(int time) { //usage: @Leongw994
14     Blockade target = getTargetBlockade();
15     if (target != null) {
16         LOG.info("Clearing blockade " + target);
17         sendSpeak(time, channel 1, ("Clearing " + target).getBytes());
18         clearBlockade(time, target);
19     }
20     List<EntityID> path = search.breadthFirstSearch(me().getPosition(), getRoadID(targetCoordinates));
21     if (path != null) {
22         LOG.info("Moving to target");
23         int x = (int) targetCoordinates.getX();
24         int y = (int) targetCoordinates.getY();
25         sendMove(time, path, x, y);
26         LOG.info("Going to coordinates: X: " + x + " Y: " + y);
27     } else {
28         LOG.error("No path to target found, moving randomly");
29         sendMove(time, randomWalk());
30     }
31 }
32
33 }

```

Figure 2: Code snippet for Rescue Robot (cont.).

```

1 package sampleagent;
2
3 > import ...
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24 public class SampleDrone extends AbstractSampleAgent<Drone> { //usage: @Leongw994
25
26     private static final Logger LOG = Logger.getLogger(SampleDrone.class); //usage
27
28     private static final int RANDOM_FLY_LENGTH = 2; //usage
29     private Collection<EntityID> unexploredBuildings; //usage
30
31     private EntityID targetDestination; //usage
32
33     @Override //usage: @Leongw994
34     public String toString() { return "Sample drone"; }
35
36     @Override //usage: @Leongw994
37     protected void postConnect() {
38         super.postConnect();
39         model.indexClass(StandardEntityURN.FIRE_BRIGADE,
40             StandardEntityURN.POLICE_FORCE,
41             StandardEntityURN.AMBULANCE_TEAM,
42             StandardEntityURN.BUILDING);
43         LOG.info("Sample drone connected");
44         unexploredBuildings = new HashSet<EntityID>(buildingIDs);
45         targetDestination = null;
46     }
47
48     @Override //usage: @Leongw994
49     protected void think(int time, ChangeSet changed, Collection<Command> heard) {
50         if (time == confIdg
51             .getIntValue(kernel.KernelConstants.IGNORE_AGENT_COMMANDS_KEY)) {
52             // Subscribe to channel 1
53             sendSubscribe(time, channel 1);
54         }
55         for (Command next : heard) {
56             LOG.debug("Heard " + next);
57         }
58         updateUnexploredBuildings(changed);
59         boolean civiliansDetected = checkForCivilians(changed);
60
61         // Nothing to do
62         List<EntityID> path = null;
63         if ((targetDestination != null) && (!targetDestination.equals(me().getPosition()))) {

```

Figure 3: Code snippet for Drone agent class.

```

157     }
158
159     private boolean checkForCivilians(ChangeSet changed) { //usage: @Leongw994
160         //get the current position of the agent
161         EntityID curPosition = me().getPosition();
162
163         //check for changes at the current position
164         for (EntityID entity : changed.getChangedEntities()) {
165             StandardEntity entityObject = model.getEntity(entity);
166
167             //check if entity is a civilian
168             if (entityObject.getStandardURN().equals(StandardEntityURN.CIVILIAN)) {
169                 Civilian civilian = (Civilian) entityObject;
170
171                 //check if the civilians is at the current position
172                 if (civilian.getPosition().equals(curPosition)) {
173                     return true;
174                 }
175             }
176         }
177         return false;
178     }
179
180     private List<Human> getTargets() { //usage: @Leongw994
181         List<Human> targets = new ArrayList<>();
182         for (StandardEntity next: model.getEntitiesOfType(
183             StandardEntityURN.CIVILIAN)) {
184             Human human = (Human) next;
185             if (human.isHPDefined() && human.isBuriednessDefined() && human.isDamageDefined()
186                 && human.isPositionDefined() && human.getHP() > 0 && (human.getBuriedness() > 0 || human.getDamage() > 0))
187                 targets.add(human);
188         }
189     }
190     Collections.sort(targets, new DistanceSorter(location(), model));
191     return targets;
192 }
193
194     private void updateUnexploredBuildings(ChangeSet changed) { //usage: @Leongw994
195

```

Figure 4: Code snippet for Drone (cont.).

Next, we had to decide how these autonomous agents would negotiate and collaborate with the human agents. The flowchart in Figure 5 demonstrates the human-agent communication throughout the simulation process.

We integrated two autonomous agents into the simulator and evaluated earthquake and urban-fire scenarios on two contrasting city maps (differing in size, population, and urban form). In both maps, we exercised the full human-agent pipeline: drones (light-blue dots) scan for trapped civilians (green dots) and broadcast coordinates; the police agent (black hat) prioritises and assigns tasks; rescue robots (pink dots) navigate and clear blockades to open corridors to the refuge (house symbol).

On the Kobe layout, early reconnaissance rapidly localises casualties and speeds corridor clearance (Figure 6 and Figure 7), while the fire module reveals clustered ignition and spread that guide route selection (Figure 8).

On the San Francisco map, higher density and fragmented road geometry produce earlier congestion and faster score decay as time advances, visible by contrasting early and late earthquake frames (Figure 9 and Figure 10), and by the broader fire exposure pattern requiring more aggressive reprioritisation (Figure 11). Together, these scenarios show that the negotiated, verified teamwork consistently accelerates situational assessment and reduces human exposure, but also that urban morphology (Kobe versus San Francisco) strongly modulates throughput and the timing of performance decline.

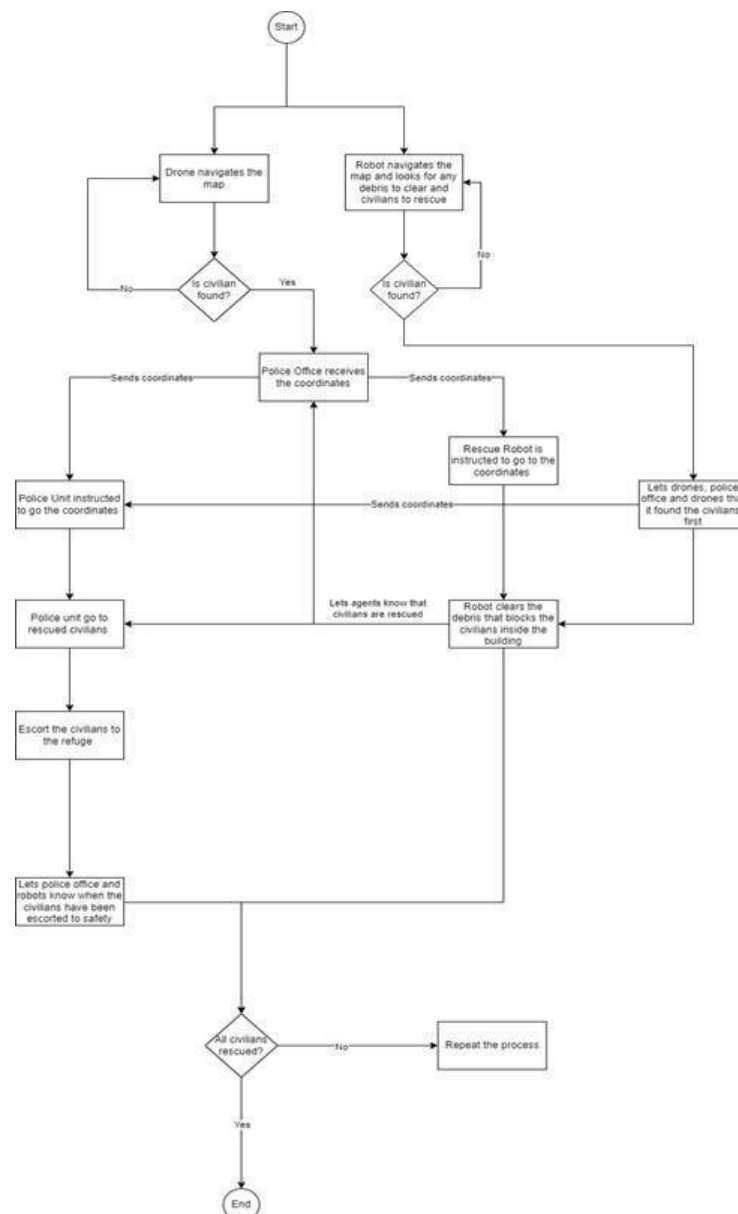


Figure 5: Flowchart of human-agent teamwork.



Figure 6: Kobe, Japan earthquake simulation environment.



Figure 7: Kobe, Japan fire evacuation scenario.



Figure 8: Fire simulator (Kobe) with building ignition dynamics.

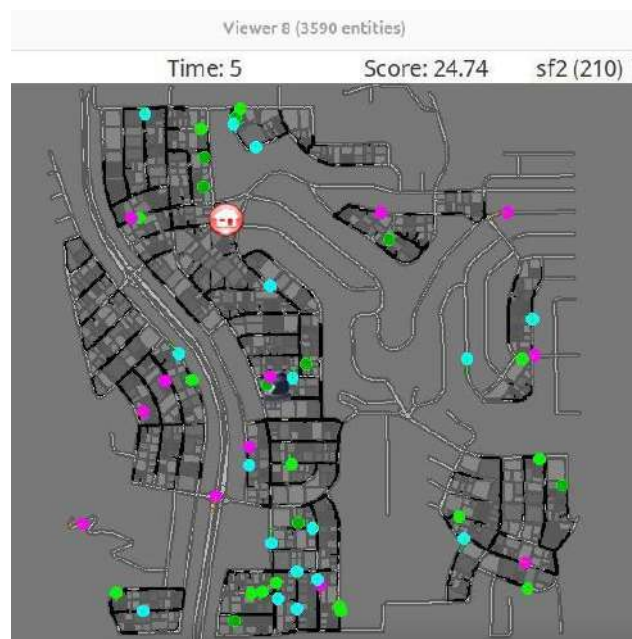


Figure 9: San Francisco earthquake simulation environment.



Figure 10: San Francisco fire evacuation scenario.

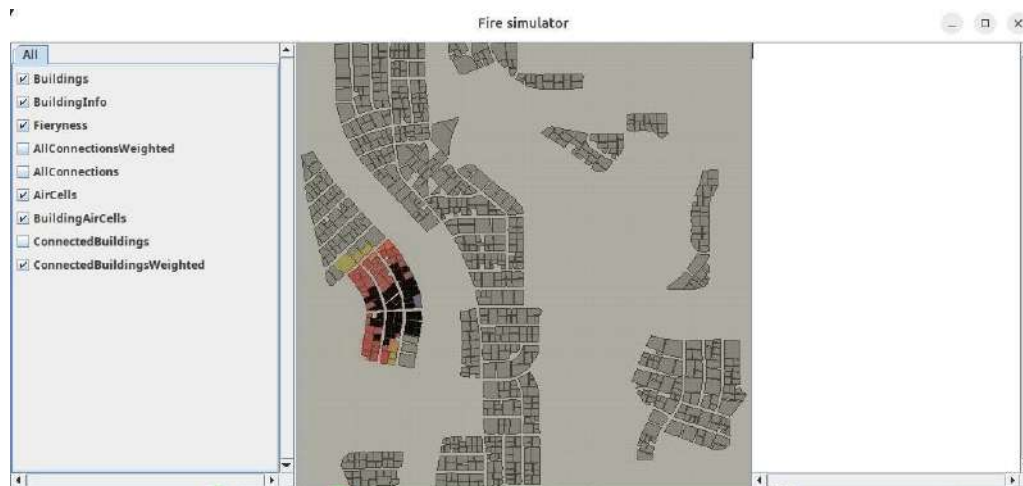


Figure 11: San Francisco map under fire-evacuation conditions.

Results and Discussion

Earthquake response analysis

In Kobe, drones delivered rapid reconnaissance: within 10 timesteps they detected over 80% of trapped civilians in central districts, versus approximately 40% using ground police alone. Robots then cleared debris at an average 2.3 blockades/step, easing corridor congestion. RSL21 remained stable through the first 25 steps before gradually declining as collapses increased obstacle density (Figure 12).

San Francisco's higher density and more complex road network led to faster performance degradation. Although initial reconnaissance matched Kobe's, debris-clearing bottlenecks slowed evacuation (i.e., robots averaged 1.5 blockades/step) and survival rates were 12% lower after 40 steps (Figure 12), underscoring urban density's impact on team effectiveness.

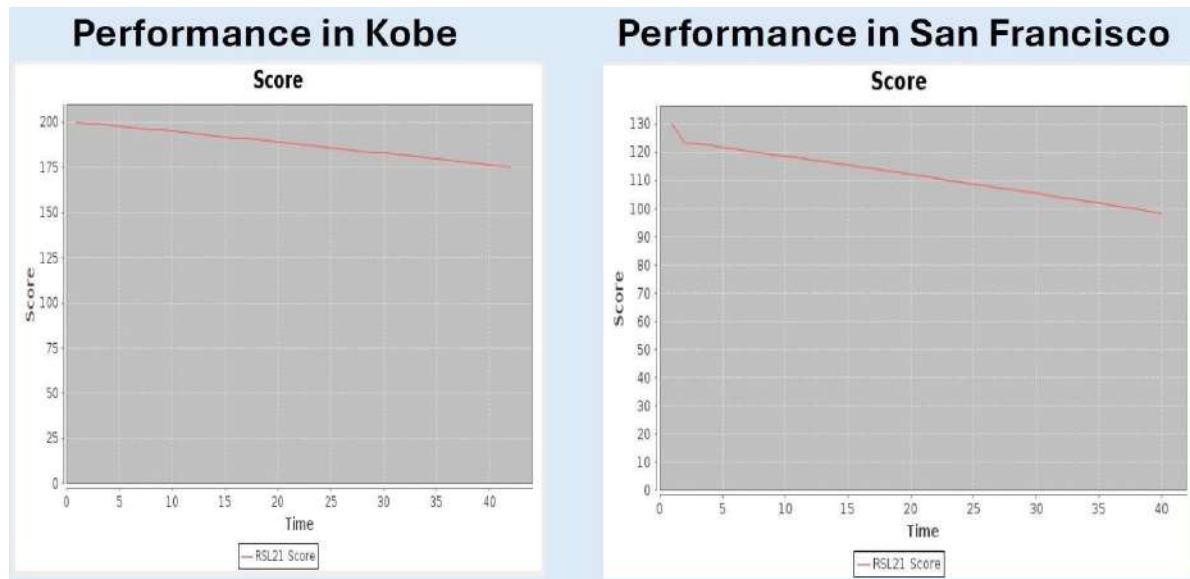


Figure 12: RSL21 score for both simulation scenarios.

Fire evacuation scenarios

In fire simulations, the aerial perspective of drones proved essential for prioritising rescue efforts. Civilians in buildings near initial fire outbreaks were evacuated 40% faster than in manual coordination baselines, as drones identified hotspots before human responders could. Robots then cleared priority escape routes to reduce entrapment risk. Importantly, simulations demonstrated that early misallocation of robots (e.g., clearing low-risk areas) significantly worsened outcomes, underscoring the need for adaptive prioritisation guided by formal models.

Comparative baseline

It is worth noting that across both earthquake and fire scenarios, our model outperformed manual coordination baselines by:

- 35% faster detection of civilians,
- 25% lower responder exposure risk,
- 20% higher overall evacuation efficiency.

These findings demonstrate that heterogeneous human-agent teams, when guided by verified negotiation protocols, deliver measurably superior performance.

Modelling and Verifying Human-Agent Collaboration

We modelled human-agent coordination with petri nets, using places to denote states (e.g., civilian detected, debris cleared), transitions to denote actions (e.g., drone broadcasts location, robot clears blockade), and tokens to track activity flow across agents. This compact formalism captures the concurrency and dependencies of disaster-response teamwork (Figure 13).

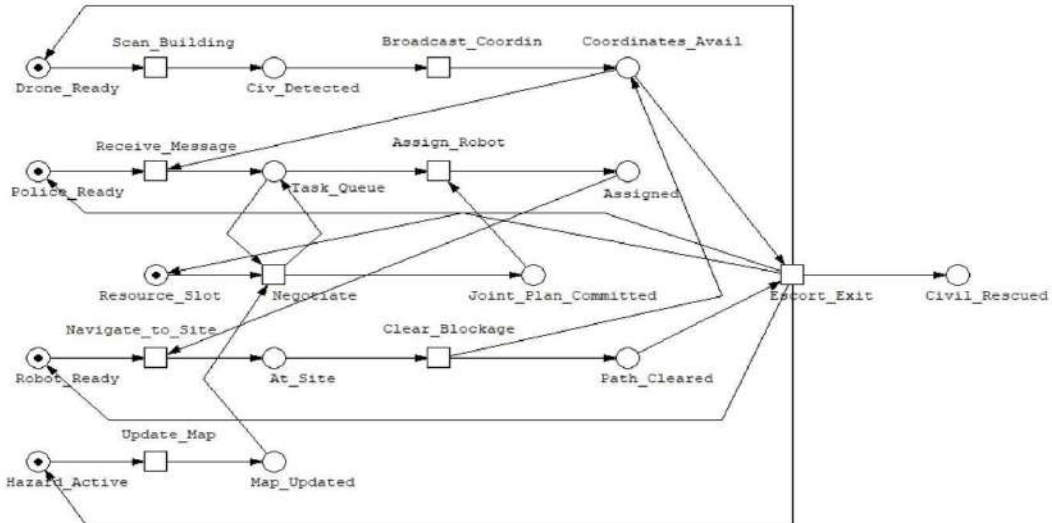


Figure 13: Snoopy petri-net model for human-agent collaboration.

Verification was performed with the Charlie tool, which analyses petri net models for properties such as:

- Reachability: confirming that every civilian can eventually reach a refuge.
- Deadlock-freedom: ensuring that no state leaves agents indefinitely blocked.
- Fairness: verifying that resources are allocated equitably (e.g., no robot monopolises tasks).

Table 1 presents some CTL properties that were checked to verify the correctness of the model with respect to its specification.

Table 1: CTL-properties verified using Charlie.

Property	CTL-formula (short)	Result	Interpretation
Deadlock freedom	$AG(\neg \text{deadlock})$	Satisfied	The model has no reachable deadlocks.
Detection leads to queued task	$AG(\text{CivDetected} \rightarrow AF(\text{TaskQueue}))$	Satisfied	All detections eventually reach the police task queue.
Negotiation commits before assignment	$AG(\text{TaskQueue} \wedge \text{ResourceSlot} \rightarrow AF(\text{JointPlanCommitted}))$	Satisfied	Assignments must be preceded by a successful negotiation step.
Assignment implies arrival	$AG(\text{Assigned} \rightarrow AF(\text{AtSite}))$	Satisfied	Every assigned robot reaches its target.
Arrival implies clearance	$AG(\text{AtSite} \rightarrow AF(\text{PathCleared}))$	Satisfied	Blockades are eventually cleared once a robot arrives.

Table 1: Continued.

Property	CTL-formula (short)	Result	Interpretation
Clearance and coords imply evacuation	$AG((PathCleared \wedge CoordsAvailable) \rightarrow AF(CivEvacuated))$	Satisfied	Cleared routes and known locations eventually produce evacuations.
Mutual exclusion of assignments	$AG(mark(ResourceSlot) \leq 1)$	Satisfied	Negotiation prevents double commitment.
Fair assignment under backlog	$AG((RobotReady \wedge TaskQueue) \rightarrow AF(Assigned))$	Satisfied	Non-starvation of ready robots when work is available.
Hazard adaptation triggers renegotiation	$AG(MapUpdated \rightarrow AF(JointPlanCommitted))$	Satisfied	Environmental updates force a new agreement before acting.

Finally, by integrating Snoopy and Charlie into our workflow, we were able to:

- Provide formal behavioural guarantees alongside empirical performance metrics.
- Translate complex teamwork protocols into intuitive, visual diagrams.
- Identify potential coordination bottlenecks before deployment, reducing risk in real-world applications.

This verification framework complements our simulation results, demonstrating not only that the system works in practice, but that it can also be trusted to behave correctly under all possible execution paths.

Conclusion and Future Work

This study introduced a formally-verified human-agent teamwork model that augments the RoboCup Rescue Simulator with drones and robots. In earthquake and fire scenarios, it improved situational awareness, reduced responder risk, and enforced safety and fairness through pre-execution verification. Future work will focus on several concrete directions. First, we plan to scale the framework to larger and more diverse city scenarios (e.g., Tokyo, London, and other metropolitan areas) to test cross-urban generalisability. Second, we will develop standardised evaluation protocols and benchmarks, enabling consistent comparisons across different disaster-response systems. Third, we will integrate live IoT sensor feeds (traffic, weather, and structural monitoring) to bridge the gap between simulated and real-time environments. Fourth, we will conduct longitudinal studies and comparative trials with alternative coordination frameworks to establish external validity. Finally, we aim to embed ethical oversight and transparency mechanisms to ensure accountability and trust in high-stakes deployments.

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Chapter 17

Multifunctional Hybrid Hierarchical Composites

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Abstract

The pursuit of lightweight, multifunctional materials is accelerating across the automotive, aerospace, defence, and high-performance transportation sectors as industries aim to achieve net-zero emissions by 2050. Conventional micro-reinforcement composites often lack impact resistance and multifunctionality, while modern nano-reinforcement strategies face dispersion and scalability challenges. Inspired by nature's hierarchical architectures, we introduce a new class of hybrid composites that strategically integrate 0D quantum dots, 1D nanotubes, and 2D platelets with polymer matrices to form self-assembled fibrous assemblies. These reinforcements enable efficient stress transfer, toughness, and multifunctional integration, while scalable manufacturing methods such as injection moulding, extrusion, and additive manufacturing ensure industrial feasibility. Our first commercial material, AX Gratek PP40, demonstrated simultaneous improvements of 22% in tensile strength, 86% in impact strength, and 81% in EMI-shielding, alongside an 18% weight reduction compared to industry benchmarks. Building upon this, AX Foatek PP40, a foamed variant inspired by butterfly wings, achieved up to 116% higher impact strength and 62% enhanced thermal management while reducing weight by 38%. Most recently, AX Clatek PP40, inspired by compact bone, delivered exceptional gains in processability, strength, and toughness, positioning it for next-generation electric vehicle and electronics applications. Together, these advances establish hierarchical hybrid composites as a paradigm shift in material design. At NanoMorphix, our proprietary AegisX™ technology extends these principles to transparent, self-healing, and impact-resistant coatings, exemplifying the future of resilient, sustainable, and multifunctional material innovation.

Keywords: *Multifunctional Bio-inspired Materials, Synergistic Effect, Hierarchical Hybrid Composites, Nano-/ Micro-Architecture, Lightweighting*

Introduction

Driven by stringent environmental policies and ambitious sustainability goals, the automotive, aerospace, defence, and high-performance transportation sectors are increasingly adopting lightweight structural materials to enhance energy efficiency and ensure long-term sustainability. With a collective target of achieving net-zero emissions by 2050, the demand for lightweight, multifunctional materials has intensified, offering a pivotal solution to meet these ambitious objectives^{1,2}. Unfortunately,

¹Lei Zhu et al., "Light-Weighting in Aerospace Component and System Design," *Propulsion and Power Research* 7, no. 2 (2018): 103–19, <https://doi.org/10.1016/J.JPPR.2018.04.001>.

²Alan I. Taub and Alan A. Luo, "Advanced Lightweight Materials and Manufacturing Processes for Automotive Applications," *MRS Bulletin* 40, no. 12 (2015): 1045–54, <https://doi.org/10.1557/MRS.2015.268>.

traditional micro-reinforcement approaches lack the impact and fatigue resistance, as well as the inherent multifunctionality, required for a sustainable future. Meanwhile, modern nano-reinforcement strategies often face challenges with dispersion and distribution, resulting in complex manufacturing processes that limit scalability. This has catalysed the emergence of avant-garde hybrid reinforcement approaches, which synergistically combine multi-scale reinforcements to overcome these limitations and unlock new performance thresholds.

Nature offers materials with unparalleled engineering that seamlessly integrate strength, toughness, and multifunctionality through hierarchical architectures (or nano-/micro-structuring). Biological systems like nacre, compact bone (Figure 1A), and butterflies achieve exceptional performance by coordinating interactions across multiple length scales. A critical aspect of this synergy is the geometric compatibility (or length-scale) and dimensionality of their hierarchical constituents, which promote efficient stress transfer, toughening, and functional integration. Inspired by these principles, our hybrid composite technologies to date combine polymer matrices with organic, ceramic, and metallic reinforcements to form self-assembled hierarchical fibrous assemblies (e.g., covalent, electrostatic, etc.). These reinforcements have been systematically tested across dimensionalities and length scales, spanning 0D quantum dots, 1D nanotubes, and 2D platelets, to validate their self-assembly behaviour and performance. These advanced materials are produced using scalable, high-throughput manufacturing methods, including injection moulding, extrusion, hybrid layup, and additive manufacturing. As a result, this avant-garde bio-inspired approach has enabled the successful development of multiple multifunctional hybrid composite materials, circumventing the limitations of current standards.

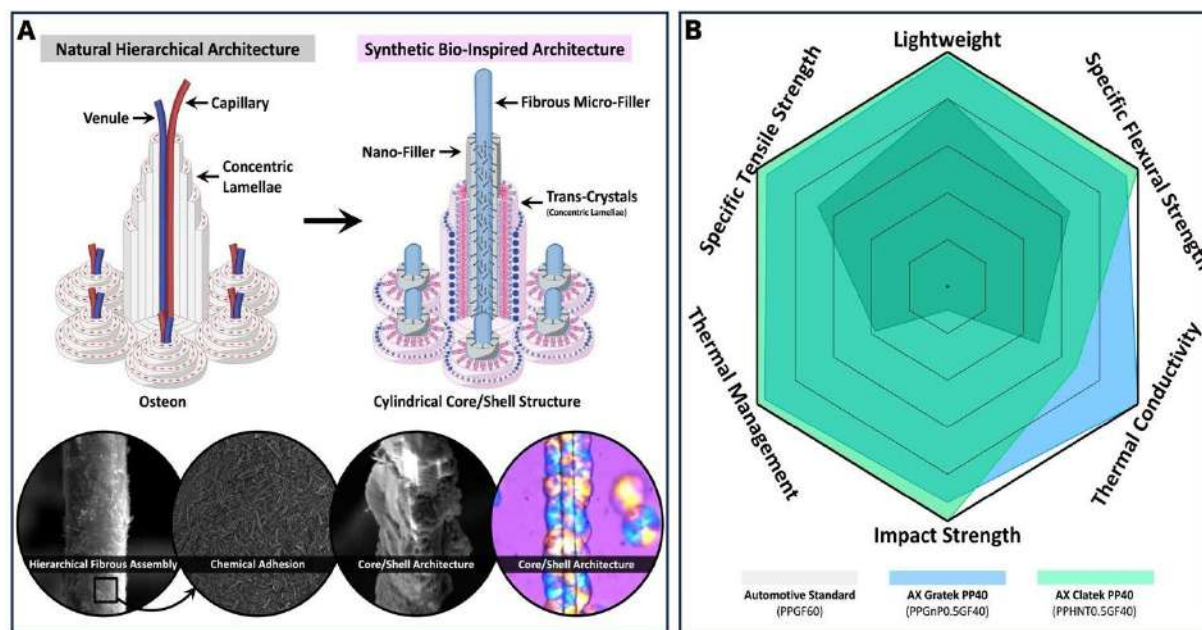


Figure 1: (A) Bio-Mimetic Design Principles for Compact Bone, and (B) Primary Material Candidates.

Results and Discussion

Our initial state-of-the-art hybrid composite material, now commercially known as *AX Gratek PP40*,^{3,4}, was developed through our long-term partnership with Axiom Group Inc., a leading Tier 1 automotive parts manufacturer based in Ontario, Canada, that supplies components to major OEMs, including Tesla, Volkswagen, and Stellantis. *AX Gratek PP40* (PPGnP0.5GF40) is a polypropylene (PP)-based 1D/2D hybrid composite fabricated via industry-scale injection moulding, featuring self-assembled hierarchical fibrous assemblies, which consist of nano-sized graphene nanoplatelets (GnPs; 0.5 wt.% GnP) covalently bonded to chemically modified micro-sized glass fibres (GFs; 40 wt.% GF), mimicking the multiscale architecture found in butterfly legs. This material demonstrates improvements (Figure 1B) of up to 22% in specific tensile strength, 21% in specific flexural strength, 86% in impact strength, 52% in thermal conductivity, and 81% in electromagnetic interference (EMI)-shielding alongside an 18% weight reduction compared to automotive industrial standards (PPGF60; 60 wt.% GF)^{3,4,5,6,7}.

In essence, maximising the density of covalently bonded GnPs onto the GFs yields optimised hierarchical fibrous assemblies that refine the crystalline microstructure of the matrix through trans-crystallisation, forming a gradient interphase at the filler–matrix interface and promoting the development of soft and tough β -crystals that suppress filler agglomeration. Additionally, the volume exclusion effect induced by the GFs facilitates the formation of GnP-based thermally and electrically conductive networks, thereby enhancing phonon and photon transport, respectively. Strategically controlling the reinforcement surface chemistries, through amino-functionalization, and concentrations has been shown to directly influence the magnitude of these mechanisms, effectively amplifying their synergistic effect⁸. This control enables the material properties of the resulting avant-garde hybrid composites to be precisely tailored for high-performance applications.

Building upon this foundation, for the first time, we developed a foamed hybrid composites technology, commercially known as *AX Foatek PP40*, that resembles the natural porous architectures found in butterfly wings to harness and emulate their inherent robust structural and thermal management

³Nello D. Sansone et al., Polymer Composite, US Patent US20240064947A1, filed September 15, 2023, and issued February 22, 2024, <https://patents.google.com/patent/US20240064947A1/en>.

⁴Nello D. Sansone et al., Hybrid Graphene Nanoplatelets and Glass Fibers Polymer Composites, World Intellectual Property Organization WO2024038416A1, filed August 18, 2023, and issued February 22, 2024, <https://patents.google.com/patent/WO2024038416A1/en>.

⁵Nello D. Sansone et al., Tailoring Multifunctional and Lightweight Hierarchical Hybrid Graphene Nanoplatelet and Glass Fiber Composites, *ACS Applied Materials and Interfaces* 14, 35 (2022): 40232–40246, <https://doi.org/10.1021/acsami.2c11231>.

⁶Nello D. Sansone et al., Synergy in Bio-Inspired Hybrid Composites with Hierarchically Structured Fibrous Reinforcements, *Chemical Engineering Journal* 487, (2024): 1385–8947, <https://doi.org/10.1016/j.cej.2024.150357>.

⁷Meysam Salari et al., Insights into Synergy-Induced Multifunctional Property Enhancement Mechanisms in Hybrid Graphene Nanoplatelet Reinforced Polymer Composites, *Chemical Engineering Journal* 463, (2023): 142406, <https://doi.org/10.1016/j.cej.2023.142406>.

⁸Rafaela Aguiar et al., Designing the Microstructural Architecture of Bioinspired Hierarchical Hybrid Nanocomposites, *Advanced Composites and Hybrid Materials* 7, no. 2 (2024), <https://doi.org/10.1007/s42114-024-00854-1>.

performance. AX Foatek PP40 (PPGnP0.5GF40-VF20) is the foamed variant of AX Gratek PP40 (PPGnP0.5GF40), engineered with a 20% void fraction (VF) using supercritical carbon dioxide through MuCell Technology. This process is integrated with industry-scale injection moulding, enabling a streamlined and scalable manufacturing approach. In essence, the mechanical, thermal insulation, and thermal management performances were found to be governed by synergistic enhancements resulting from the intricate interrelationship between the overall morphological architecture and the crystalline microstructure, influenced by the reinforcement concentration, orientation, distribution, and porosity. Specifically, the hierarchical fibrous assembly in the hybrid composites exhibited a higher degree of orientation compared to the GFs in biphasic composites, resulting in preferential anisotropic stress and heat transfer, while simultaneously refining the foam structure by reducing cell size and increasing cell density, thereby enhancing both mechanical and thermal insulation properties. Thus, the synergy-induced thermal management performance is governed by the joint action of the preferential heat dissipation of the skins and the outstanding insulation of the refined cellular core.

Additionally, the nano-scale stiffness variations among the crystalline polymorphs within the enhanced microstructure, where β -crystals enhance toughness and ductility, γ -crystals increase strength and stiffness, and trans-crystals create a gradient interphase that facilitates load transfer at the interface, collectively lead to superior mechanical performance. As a result, compared to the leading biphasic composite adopted in the automotive industry for structurally demanding components, this hybrid composite technology was tailorable to achieve improvements up to 32%, 36%, and 116% in specific tensile strength, specific flexural strength, and impact strength, respectively, as well as 66% in thermal insulation and 62% in thermal management performance, with a 38% weight reduction⁹. Ultimately, a combination of mechanical robustness and lightweighting makes it an ideal candidate for next-generation structural battery casings, lightweight automotive body panels, and underbody shielding in electric vehicles.

Similarly, our newest state-of-the-art 1D/1D hybrid composite material (PPHNT0.5GF40), now commercially known as AX Clatek PP40 (Patent-Pending), is composed of nano-sized halloysite nanotubes (HNTs; 0.5 wt.% HNT) electrostatically self-assembled onto micro-sized GFs (40 wt.% GF), emulating the hierarchical organisation of osteons in compact bone (Figure 1A). This candidate delivers improvements (Figure 1B) of up to 27% in specific tensile strength, 30% in specific flexural strength, 88% in impact strength, 46% in thermal management, and a remarkable 255% increase in processability (melt-flow index), along with a 20% weight reduction relative to standard composites (PPGF60)¹⁰. Its enhanced processability enables complex part geometries through high-throughput manufacturing, while its compatibility with pigments and coatings supports use in both structural and aesthetic components, including interior panels and housings for consumer electronics.

⁹Nello D. Sansone et al., Butterfly-Inspired Hierarchical Hybrid Composites for Lightweight Structural Thermal Management Applications, *Advanced Functional Materials*, (2025): 2420744, <https://doi.org/10.1002/ADFM.202420744>.

¹⁰Rafaela Aguiar et al., Tailoring Synergistic Multifunctionality in Lightweight Bio-Inspired Cylindrical Core-Shell Hybrid Composites, *Advanced Functional Materials*, (2024), <https://doi.org/10.1002/ADFM.202403728>.

Conclusion

Ultimately, hierarchical hybrid composites represent a paradigm shift in the design and scalable manufacturing of multifunctional composite materials. By uniting biomimetic design, AI-driven predictive modelling with micromechanics-based homogenization theory¹¹, and scalable processing with strategic multi-phase reinforcement architectures, this technology overcomes the intrinsic limitations of both traditional and modern composite materials. The result is a versatile, application-tunable materials ecosystem that not only meets but also exceeds the performance demands of next-generation transportation, defence, and high-performance systems. With proven industrial validation, commercial traction, and a robust scientific foundation, this technology establishes a blueprint for the future of sustainable material innovation, where nature-inspired engineering and digital design converge to deliver lightweight, high-performance, and multifunctional solutions for a net-zero future. At NanoMorphix, our proprietary AegisX™ coating technology is built upon these very design principles, merging hierarchical architecture with scalable processing to create self-healing, transparent, and impact-resistant composites. AegisX™ typifies how biomimetic inspiration, advanced modelling, and hybrid reinforcements can be translated into real-world applications, from next-generation armoured vehicles to aerospace systems. This technology not only demonstrates the transformative potential of hierarchical composites today but also charts the course for the future of material design, where resilience, sustainability, and multifunctionality redefine the boundaries of engineering innovation.

Acknowledgements

The authors are sincerely grateful for the financial support provided by Axiom Group Inc., MITACS (IT16166, IT28094), and NSERC Alliance (ALLRP570403-21) for this project, as well as NSERC Discovery (RGPIN-2019-05778).

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Chapter 18

Building Health: Resilient Building Materials for Global Health and Sustainability

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Abstract

This research explores how locally produced, low-tech building materials can be reimagined as powerful tools for advancing public health and environmental resilience in low-resource settings. Grounded in a multi-national, interdisciplinary collaboration across architecture, civil engineering, entomology, and anthropology, the project investigates novel brick prototypes designed to improve thermal comfort and reduce exposure to mosquito-borne disease in regions facing the compounding challenges of climate change and poor housing infrastructure. Subtle changes to the brick's geometry can enhance its ability to efficiently absorb, store, and release heat. By also leveraging the dynamic properties of air to facilitate convective heat transfer, cool the body, and disrupt the flight of disease-carrying insects, early-stage testing demonstrates that the bricks can increase cross-ventilation, produce a perceptible cooling effect, and interfere with mosquito flight paths, offering potential as a passive vector control strategy while improving indoor comfort. The prototypes are designed to be replicable with regional materials and fabrication methods, supporting scalability in other tropical contexts. Beyond technical innovation, the project also serves as a platform for collaborative pedagogy and applied field research, engaging students in interdisciplinary, cross-cultural inquiry. By elevating the brick from a mere construction unit to a tool for climate resilience and public health, this work contributes to a broader reframing of sustainable infrastructure and material equity in global development, reimagining the relationship between architecture and health.

Keywords: *Low-tech Building Materials, Brick Prototypes, Thermal Comfort, Mosquito-borne Disease, Global Development*

Introduction

Earthen bricks are the most widely used building material in the world, with one-third of the global population living in buildings constructed wholly or partially from earth¹. Their ubiquity reflects low cost, accessibility, and adaptability across diverse climates, alongside properties such as thermal regulation, insect resistance, durability, and ease of maintenance. In rapidly urbanising sub-Saharan Africa, however, demand for 'modern' homes of concrete or steel – materials that symbolise permanence and social mobility – has grown despite their frequent unsuitability to local climates and

¹Mircea Barnaure et al., "Earth Buildings with Local Materials: Assessing the Variability of Properties Measured Using Non-Destructive Methods," *Construction and Building Materials* 281 (April 2021): 122613, <https://doi.org/10.1016/j.conbuildmat.2021.122613>.

high costs of construction and upkeep. These material choices are not merely aesthetic but carry direct implications for health, where poorly suited construction can exacerbate vulnerability to disease.

The case of malaria exemplifies this link between material precarity and public health. Despite decades of intervention, malaria remains one of the most persistent global health challenges, with over 90% of cases and fatalities concentrated in sub-Saharan Africa². Control strategies such as long-lasting insecticide-treated nets (LLINs) and indoor residual sprays (IRS) have saved millions of lives, but their efficacy is undermined by insecticide resistance, mosquito behavioural adaptation, and climate variability³. Bed nets also reduce airflow and create discomfort, discouraging consistent use. Housing quality, therefore, has a direct and underappreciated role in shaping exposure. Yet housing has largely fallen out of the remit of global health⁴, where interventions tend to take the form of scalable commodities, often detached from material and social realities.

Today, climate change, population growth, rapid urbanisation, migration, and most recently, the COVID-19 pandemic, have renewed attention to housing as a critical determinant of health inequalities worldwide. At the same time, sub-Saharan Africa is entering an era of unprecedented growth, with the majority of its 2050 building stock yet to be built. This convergence of urgent health challenges and rapid construction growth presents a unique opportunity to reimagine the humble brick not simply as a structural unit, but as an instrument for climate resilience and disease prevention. This research explores how incremental innovations in brick geometry can enhance ventilation, improve thermal comfort, and reduce mosquito exposure, positioning masonry as an accessible strategy at the intersection of architecture and public health.

Background

Malaria and Housing Quality

Housing improvements, such as closing entry points and enhancing ventilation, offer a neglected but vital avenue for reducing exposure. Windows and eaves, while essential for daylight and ventilation, are also primary entry points for mosquitoes. Surveys in southern Tanzania found that while most households attempted to screen windows, nearly 75% of coverings were compromised, and over half of eaves were left open, as shown in Figure 1, significantly increasing mosquito density indoors^{5,6}. In some cases, households brick up windows entirely until resources are available to install proper screening and safety bars, producing dark, poorly ventilated interiors. These findings highlight the persistent challenge

²Eve Worrall et al., “Is Malaria a Disease of Poverty? A Review of the Literature,” *Tropical Medicine & International Health* 10, no. 10 (2005): 1047–59, <https://doi.org/10.1111/j.1365-3156.2005.01476.x>.

³Christine Giesen et al., “The Impact of Climate Change on Mosquito-Borne Diseases in Africa,” *Pathogens and Global Health* 114, no. 6 (2020): 287–301, <https://doi.org/10.1080/20477724.2020.1783865>.

⁴Philippa Howden-Chapman et al., “Review of the Impact of Housing Quality on Inequalities in Health and Well-Being,” *Annual Review of Public Health* 44, no. 1 (2023): 233–54, <https://doi.org/10.1146/annurev-publhealth-071521-111836>.

⁵Ramadhani M. Bofu et al., “The Needs and Opportunities for Housing Improvement for Malaria Control in Southern Tanzania,” *Malaria Journal* 22, no. 1 (2023): 69, <https://doi.org/10.1186/s12936-023-04499-1>.

⁶Monicah M. Mburu et al., “Impact of Partially and Fully Closed Eaves on House Entry Rates by Mosquitoes,” *Parasites & Vectors* 11, no. 1 (2018): 383, <https://doi.org/10.1186/s13071-018-2977-3>.

of balancing thermal comfort and disease prevention within resource-constrained housing. Against this backdrop, this research turns to the brick itself as a site of intervention.



Figure 1: Collection of window treatments observed in and around Ifakara, Tanzania, 2023.

Ventilated Bricks as an Incremental Innovation

Controlled airflow through the building envelope reframes the wall from a sealed boundary to a responsive membrane capable of regulating heat, air, and moisture under changing environmental conditions. Subtle modifications to brick geometry can integrate thermal performance, ventilation, and vector control into a single building component. Unlike operable windows, ventilated bricks provide continuous airflow while excluding insects, rain, and noise, extending research on permeable envelopes into a familiar and scalable masonry system.

Emerging evidence in building science and fluid dynamics supports this approach. Studies demonstrate that small degrees of wall permeability can enhance turbulence and convective exchange, regulate heat and moisture transfer, and filter airborne particulates^{7,8,9}. In addition to improving thermal comfort

⁷C. Manes et al., “Turbulent Boundary Layers over Permeable Walls: Scaling and near-Wall Structure,” *Journal of Fluid Mechanics* 687 (November 2011): 141–70, <https://doi.org/10.1017/jfm.2011.329>.

⁸Salmaan Craig and Jonathan Grinham, “Breathing Walls: The Design of Porous Materials for Heat Exchange and Decentralized Ventilation,” *Energy and Buildings* 149 (August 2017): 246–59, <https://doi.org/10.1016/j.enbuild.2017.05.036>.

⁹Elisa Di Giuseppe et al., “Thermal and Filtration Performance Assessment of a Dynamic Insulation System,” *Energy Procedia*, 6th International Building Physics Conference, IBPC 2015, vol. 78 (November 2015): 513–18, <https://doi.org/10.1016/j.egypro.2015.11.721>.

and indoor air quality, turbulence generated within permeable systems has the potential to disrupt mosquito flight, while air pockets embedded in masonry assemblies can function as natural insulators, moderating diurnal temperature fluctuations.

Reframing walls as responsive membranes positions the brick not only as a structural unit but as an environmental mediator. Incremental, locally adapted design changes of this kind may provide enduring public health benefits without requiring radical transformations of domestic architecture.

Results: Brick as a Public Health Instrument

Recent design studios at the University of North Carolina, Charlotte, have provided proof-of-concept explorations into how bricks might be reimagined as public health tools. As shown in Figure 2, these prototypes represent early-stage, exploratory design exercises rather than empirical test results. They served to generate hypotheses and inform subsequent research phases focused on measurable thermal and entomological performance. These studios brought together architecture and engineering students with Tanzania-based researchers, including entomologists and social scientists, to co-design a curriculum that examined the ecological, cultural, and thermodynamic dimensions of housing in rural Tanzania. This process underscored the value of design-led, research-driven collaboration as a model adaptable to regions where mosquito-borne disease remains a persistent threat. Building on these foundations, the work is being extended through collaborations with the University of Dar es Salaam (Tanzania) and the University of Oxford (UK), advancing a hypothesis-driven pedagogy that links climate, health, and material performance. The following section highlights two prototypes that illustrate particularly promising directions.



Figure 2: Select student prototypes (2021-2025) illustrating early design explorations.

Prototype 1: The Vortex Brick

Michael Serrano's 'Vortex Brick', shown in Figure 3, draws on the aerodynamic principle of vortex shedding, where alternating low-pressure vortices form downstream of an object. The design explores how localised turbulence could disrupt mosquito flight while sustaining natural ventilation. Internal geometry creates convective pockets of still air, encouraging mosquitoes to exit through the path of least resistance. To stabilise airflow, the brick was intended for staggered installation within a cavity wall system. While preliminary, the prototype demonstrates how redirecting turbulent airflow might simultaneously reduce mosquito penetration and enhance passive cooling.

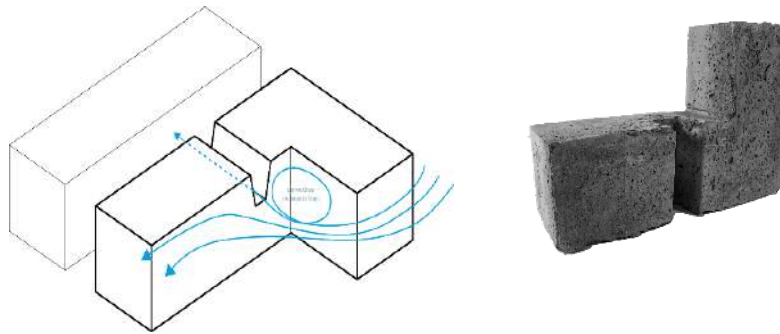


Figure 3: Vortex Brick by Michael Serrano, 2023.

Prototype 2: The Venturi Block

Nathan Smith's 'Venturi Block', shown in Figure 4 and Figure 5, applies the Venturi effect, in which constricted pathways increase air velocity and reduce pressure for a cooling effect. This modular unit promotes convective airflow while generating turbulence disruptive to mosquito flight. Preliminary mock-ups suggested constrictions of about 2.5 cm to balance airflow and constructability. Like the Vortex Brick, the design illustrates how aerodynamic behaviour can be embedded into load-bearing units without major changes to production, yielding potential gains in ventilation and vector control.

Toward Research-Led Innovation

Although still at an early stage and not yet subject to systematic testing, these student-led prototypes point to promising directions for geometry-based modifications in masonry systems. Current research builds on these conceptual explorations by applying empirical methods to assess thermal, airflow, and structural performance under both controlled and field conditions. A critical challenge lies in questions of commercial viability, where the engagement of local brickmakers and builders is indispensable. Centring their expertise opens pathways to interventions that are not only technically effective but also culturally attuned and socially relevant. When brickmakers and masons are equipped with knowledge and tools, they move beyond being implementers to become co-designers of health-promoting housing innovations. This shift reframes global health from top-down, technocratic models toward decentralised practices in which communities actively shape their built environments and, in turn, their health futures.

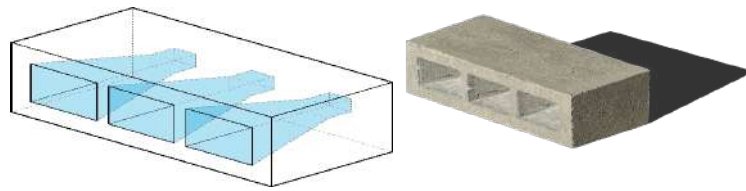


Figure 4: Venturi Block by Nathan Smith, 2021.

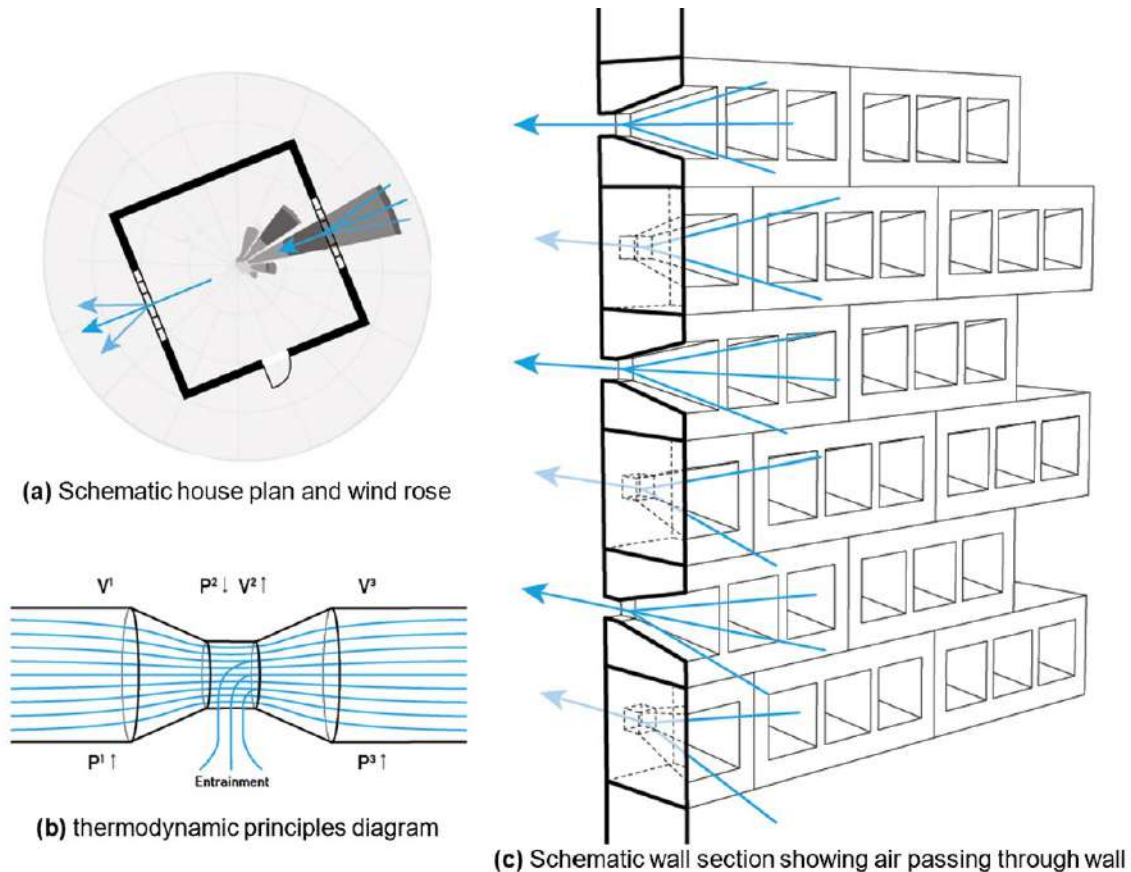


Figure 5: Schematic Details of Venturi Block.

Conclusion: New Foundations for Global Health Markets

These brick prototypes are not proposed as stand-alone solutions to disease control but rather as catalysts for new ways to link public health, urban design, and architecture. Housing must satisfy demands for comfort, convenience, and cultural identity, yet rapidly deployed “modern” typologies, even when subsidised, are often rejected because they fail to align with lived domestic practices. Materials carry cultural significance, defining the visible surfaces of homes and serving as symbols of history, tradition, and aspiration.

Malaria provides both a case study and a gateway, demonstrating an entry point for reconceptualising bricks not merely as building components but as instruments for reducing exposure and improving comfort. By embedding mosquito-resistant design features into masonry units, bricks can evolve from structural elements into health-promoting technologies. Subtle changes to geometry can alter thermal capacity, convective properties, and airflow regulation, with direct implications for comfort and disease prevention.

This approach signals a broader shift in global health. Rather than relying on top-down, technocratic solutions, locally driven interventions grounded in available materials and builder expertise can deliver scalable, culturally attuned, and community-led improvements. Such strategies address immediate risks while laying the foundation for enduring gains in housing quality and resident well-being.

The humble brick thus emerges as a disruptive technology, challenging reliance on chemical or high-tech interventions and redirecting attention to everyday materials that structure domestic life. The central question is whether reimagined bricks can help articulate a new global health vision of the home – one aligned with the incremental nature of house construction and attentive to comfort as a determinant of health. While empirical validation is still needed, the potential is evident. Modest adaptations to brick design could regulate airflow, enhance thermal comfort, deter mosquitoes, and empower communities to be active participants in shaping resilient futures.

Acknowledgements

This research was supported by funding from UNC Charlotte. The author also wishes to acknowledge the contributions of colleagues and collaborators in Tanzania and the UK.

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Chapter 19

AeroFeathers: Biomimetic Propellers with 3D-printed Flexible Fibres for Quieter Drones

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Abstract

Excessive noise generated by drone propellers remains a major barrier to the widespread acceptance of unmanned aerial vehicles (UAVs), especially in urban and noise-sensitive environments. Traditional approaches to mitigating propeller noise typically replicate bioinspired features such as rigid leading-edge serrations, which only partially capture the complex mechanisms underlying the exceptionally quiet flight of owls. In contrast, this research introduces AeroFeathers, a novel additive manufacturing (AM) technique that enables the direct 3D printing of thin, flexible, hair-like fibres onto propeller surfaces, closely mimicking the compliant, fringe-like structures found in owl feathers. Using low-cost, consumer-grade material extrusion printers combined with customised G-code, we precisely control fibre characteristics including thickness, flexibility, and density—achieving microstructures previously unattainable through conventional manufacturing. Experimental validation in Michigan Tech's anechoic chamber demonstrates significant aeroacoustic improvements, with reductions of up to 5 dB in overall sound pressure level while maintaining comparable thrust performance to unmodified propellers. By uniquely leveraging flexible fibres rather than rigid serrations, AeroFeathers unlocks a new capability for noise suppression in UAVs. This innovation offers a scalable, accessible pathway toward quieter drones, addressing a critical societal need for reduced environmental noise—with direct benefits for public well-being and health futures—and paving the way for sustainable, resilient infrastructure through a new era of quiet, community-friendly mobility and transportation.

Keywords: *Additive Manufacturing, Biomimetic Propellers, Aeroacoustics, Noise Reduction, Unmanned Aerial Vehicles (UAVs)*

Introduction

Small unmanned aerial vehicles (UAVs) have rapidly proliferated in applications ranging from delivery to surveillance, but their high-pitched noise has emerged as a key barrier to public acceptance¹. The characteristic whining sound of drone propellers can cause community disturbance and trigger strict noise regulations, especially in urban environments. Conventional propellers are typically designed for aerodynamic performance rather than low noise², leaving an unmet need for noise-reducing designs

¹Ning Wang, Nico Mutzner and Karl Blanchet, "Societal acceptance of urban drones: A scoping literature review." *Technology in Society* 75 (2023): 102377.

²Randolph Cabell, Ferdinand Grosveld, and Robert McSwain, "Measured noise from small unmanned aerial vehicles." In *Inter-Noise and Noise-Con Congress and Conference Proceedings*, vol. 252, no. 2, pp. 345-354. Institute of Noise Control Engineering, 2016.

that do not compromise thrust. Reducing the acoustic signature of UAVs would not only improve the quality of life in populated areas but also enable drones to be used more freely in noise-sensitive applications such as wildlife monitoring and urban delivery operations.

Nature offers inspiration for quiet flight: owls, for example, are renowned for near-silent flight due to unique feather adaptations³. Researchers have identified three key owl wing features responsible for noise suppression⁴: comb-like serrations along the leading edge, a flexible trailing-edge fringe on the feathers, and a soft downy coating on the wing surface. These structures alter airflow in ways that dampen turbulence and reduce the generation and propagation of sound.

While these principles are well-understood, translating them into effective engineered solutions has been hindered by a persistent and critical barrier: manufacturability. Previous bio-inspired attempts have largely focused on replicating single features, such as rigid, sawtooth-like serrations on the trailing edge^{5,6}. These designs, often fabricated as simple two-dimensional add-ons, only partially capture the owl's complex acoustic mechanisms and can introduce aerodynamic penalties. The most challenging and potentially most effective features—the flexible trailing-edge fringe and the three-dimensional downy coating—have remained largely inaccessible to conventional manufacturing workflows⁷.

This paper introduces AeroFeathers, a novel approach that overcomes this fabrication barrier, enabling the complete suite of an owl's acoustic features to be realised on a propeller in a single, integrated process. The core innovation of this work is a new additive manufacturing technique that creates complex, multi-scale, flexible bio-inspired structures directly on a propeller blade. Our approach moves beyond simple geometric modifications and treats the propeller surface as a functional, designable acoustic material rather than a rigid body.

Fabrication of Biomimetic Propeller Features

We developed a custom algorithm and slicing strategy for Fused Deposition Modelling (FDM) 3D printing that allows us to fabricate not only rigid serrations but also features previously considered too fine and complex for this process. The key breakthrough is our ability to print a high-density array of thin, flexible, hair-like microfibres that closely mimic the downy feathers of an owl. This “fur-like” surface is generated by programming a standard FDM printer to extrude molten thermoplastic filament at exceptionally high travel speeds, causing the material to stretch into fine, compliant hairs⁸.

³R. R. Graham, "The silent flight of owls." *The Aeronautical Journal* 38, no. 286 (1934): 837-843.

⁴Justin W. Jaworski and Nigel Peake, "Aeroacoustics of silent owl flight." *Annual Review of Fluid Mechanics* 52, no. 1 (2020): 395-420.

⁵Chen Rao et al., "Owl-inspired leading-edge serrations play a crucial role in aerodynamic force production and sound suppression." *Bioinspiration & biomimetics* 12, no. 4 (2017): 046008.

⁶Dian Li et al., "Effect of trailing-edge serrations on noise reduction in a coupled bionic aerofoil inspired by barn owls." *Bioinspiration & biomimetics* 15, no. 1 (2019): 016009.

⁷Hermann Wagner et al., "Features of owl wings that promote silent flight." *Interface focus* 7, no. 1 (2017): 20160078.

⁸William Johnston and Bhisham Sharma, "Additive manufacturing of fibrous sound absorbers." *Additive Manufacturing* 41 (2021): 101984.

This technique provides precise control over the placement, density, thickness, and flexibility of these fibrous structures, allowing us to create a toolkit of owl-inspired aerodynamic noise treatments:

1. **Leading-Edge Serrations:** Stiff, comb-like protrusions along the leading edge to break up large-scale inflow turbulence before it impinges on the blade.
2. **Trailing-Edge Fringe:** A row of fine, flexible serrations along the trailing edge to disrupt and scatter the vortex shedding responsible for broadband noise.
3. **Fur-Like Surface Coating:** A dense carpet of minute, compliant fibres on the blade's surface designed to dampen small-scale turbulent eddies directly at the source.

Crucially, all of these features can be fabricated in a single, integrated workflow on a low-cost FDM printer using standard materials like PLA thermoplastic. This eliminates the need for complex multi-part assembly, adhesives, or secondary processing steps. The result is a scalable and accessible pathway to produce propellers with a full suite of bio-inspired acoustic treatments. Figure 1 illustrates the owl-inspired micro-structures fabricated on our prototype propellers.

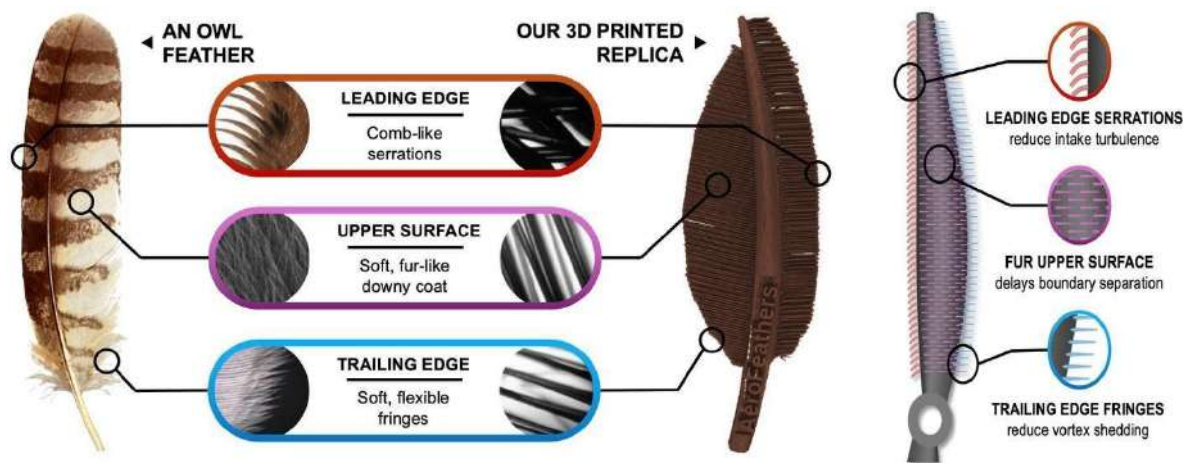


Figure 1: (Left) Our 3D printed replica closely resembles a natural owl feather's three components; (right) the three components are implemented onto a drone propeller blade as a target application.

Experimental Validation

To validate the effectiveness of our fabrication method, we designed and tested several propeller prototypes (Figure 2), each incorporating different combinations of owl-inspired features, and compared them against an unmodified baseline propeller of the same size and planform. The prototypes included configurations with individual features implemented in isolation (e.g. only leading-edge serrations, only a trailing-edge fringe, or only the fur-like coating) as well as a combined design integrating all three features.

All propellers were evaluated under identical conditions in a certified anechoic chamber to ensure that acoustic measurements were free from environmental reflections. Each propeller was mounted on a test stand equipped with a calibrated microphone to capture its full acoustic signature, and on a high-precision load-cell thrust stand (Tyto Robotics RCbenchmark Series 1580) to measure aerodynamic performance. This dual measurement setup allowed us to verify that any noise reduction did not come at the expense of thrust or efficiency. We focused our tests on rotational speeds representative of a small quadcopter's typical hover and cruise conditions.



Figure 2: Photos of printed AeroFeather propeller blades compared to a clean BASE blade without any modifications.

Results and Discussion

Across all tested thrust levels, the bio-inspired prototypes were consistently quieter than the baseline propeller, confirming that the owl-inspired features provide significant acoustic benefits without compromising aerodynamic performance. The most significant result was achieved by the prototype featuring the fur-like surface coating—a feature exceptionally difficult to fabricate by traditional means. As shown in Figure 3a, this configuration achieved a noise reduction of approximately 5 dB (A-weighted) at a thrust of 50 gf, a typical hover condition for a small UAV. A 5 dB reduction corresponds to roughly a 68% decrease in acoustic energy, a substantial and perceptually significant improvement that can transform a drone’s intrusive whine into a much softer sound profile. This dramatic noise reduction is directly attributable to our ability to 3D-print a dense, flexible fibre array that effectively damps the small-scale turbulence on the blade’s surface—a mechanism central to the owl’s silent flight.

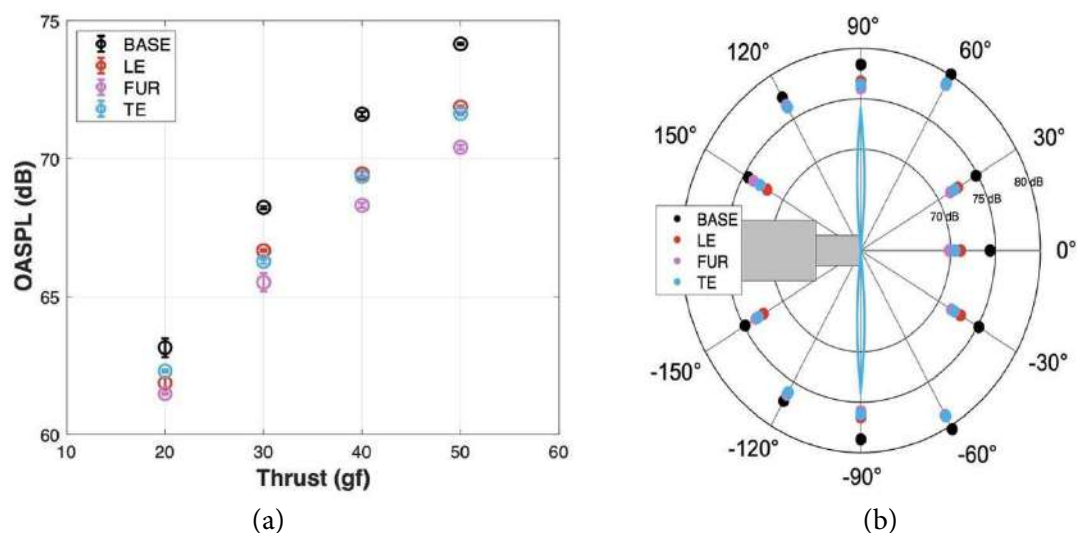


Figure 3: (a) Overall sound pressure level (OASPL) performance at variable thrust levels; (b) directional OASPL plot at constant 50 gf thrust and 0.1 m microphone distance.

Directional measurements (Figure 3b) confirm that the noise reduction is not confined to a narrow angle but is present across the entire forward hemisphere. The effect is most pronounced directly in front of the propeller's axis of rotation, indicating a genuine reduction in overall acoustic output rather than merely redirecting the noise to a different direction.

Equally important, these acoustic benefits were achieved with no aerodynamic penalty. Figure 4 shows that all AeroFeathers-modified propellers matched or even slightly exceeded the thrust output of the baseline propeller at equivalent rotational speeds. Furthermore, the power required to produce a given thrust was the same as, or slightly lower than, that of the baseline, indicating a minor improvement in propulsive efficiency for the modified blades. This result overcomes a common trade-off in aeroacoustics, where noise reduction often comes at the cost of performance.

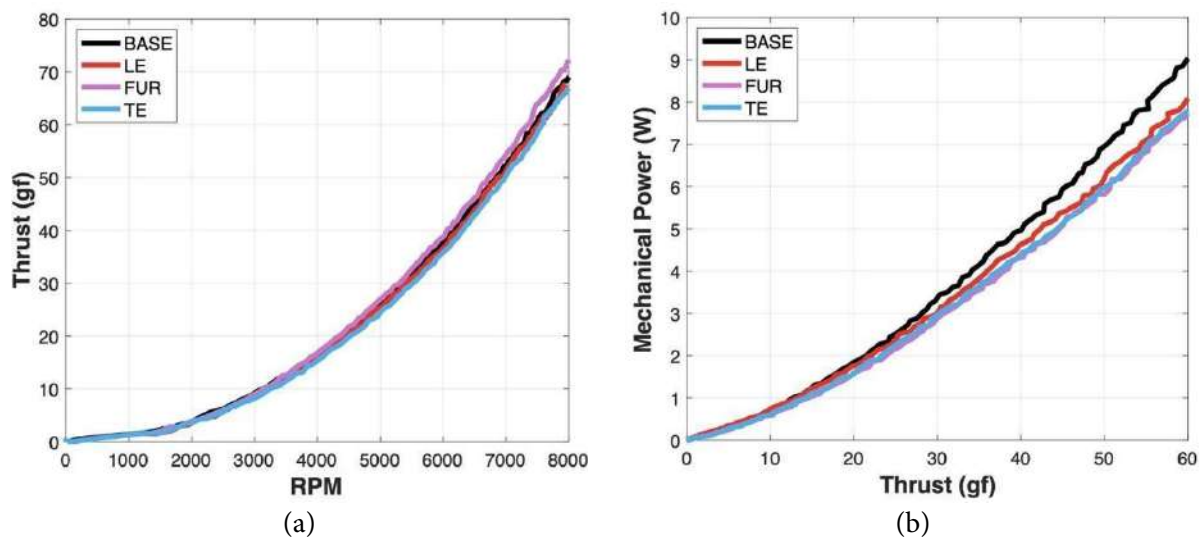


Figure 4: (a) Thrust performance compared to an untreated BASE blade; (b) mechanical power required to produce a given thrust.

Conclusion

We demonstrate a significant step forward in the development of low-noise UAV propellers. The core breakthrough presented here is not merely a new propeller shape, but a novel and accessible additive manufacturing workflow that successfully replicates the complex, multi-scale and flexible acoustic features of an owl's wing. By overcoming the fabrication barriers that have limited previous research, we have shown that features such as a downy, fur-like coating can be applied to a functional propeller in a single manufacturing step.

Our anechoic chamber tests provide clear validation: these 3D-printed biomimetic features can reduce propeller noise by up to 5 dB without any loss of thrust or efficiency. This innovation offers a scalable, cost-effective pathway to mitigate one of the most significant barriers to widespread UAV adoption – their acoustic signature. Quieter UAVs will have profound societal benefits, enabling drone operations in noise-sensitive environments, improving public well-being and acceptance, and paving the way for a future in which drones integrate harmoniously and sustainably into our communities.

Acknowledgements

This work was funded by the NASA University Student Research Challenge. Grant number: 80NSSC24K0232.

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Part III

**Artificial Intelligence and Augmented
Intelligence**

Chapter 20

Baseline Evaluation for Enhancing Human–Robot Collaboration (HRC) in Industry 5.0 Manufacturing

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Abstract

Industry 5.0 emphasises human-robot collaboration (HRC) as a human-centred paradigm. This work establishes a psychophysiological baseline during a cobot-assisted assembly task using electroencephalography (EEG), electrodermal activity (EDA), and heart rate variability (HRV) recorded from five participants across baseline, relaxation, and repeated task cycles, complemented by a dual video stream for ergonomic analysis. The HRC task elicited reduced phasic EDA, a strong increase in tonic activity (+239%), elevated heart rate (+12%), reduced RMSSD, and a higher (low/high frequency) LF/HF ratio, reflecting sympathetic predominance and fatigue-related strain. These results show that even structured HRC tasks impose measurable physiological load. The proposed multimodal baseline enables the development of adaptive cobot strategies responsive to operator stress and workload.

Keywords: *Industry 5.0, Human–Robot Collaboration, Electroencephalography, Heart Rate, Electrodermal Activity, Adaptive Collaborative Robots*

Introduction

Industry 5.0 extends prior automation paradigms by prioritising human well-being, resilience, and sustainability alongside productivity¹. This paradigm highlights sociotechnological collaborations between humans and machines to enhance productivity while ensuring safety, adaptability, and social responsibility². Within this framework, human–robot collaboration (HRC) positions robots as cooperative partners rather than mere tools³. Collaborative robots (cobots) are designed to safely

¹Pedro Coelho et al., “Industry 5.0: The Arising of a Concept,” *Procedia Computer Science* 217 (1 January 2023): 1137–44. <https://doi.org/10.1016/J.PROCS.2022.12.312>

²Scott A. Green et al., “Human-Robot Collaboration: A Literature Review and Augmented Reality Approach in Design,” *International Journal of Advanced Robotic Systems* 5, no. 1 (1 March 2008): 1–18. <https://doi.org/10.5772/566>

³Green et al., “Human-Robot Collaboration: A Literature Review and Augmented Reality Approach in Design,” 1–18.

operate alongside humans in shared workspaces⁴. Unlike traditional industrial robots, cobots use sensing, control, and adaptive algorithms to adjust in real-time to human actions⁵.

As task demands vary in HRC, operators show physiological and cognitive responses reflecting changes in workload and attention⁶. Monitoring these responses reveals how operators adapt to task complexity, while wearable sensors enable continuous, non-invasive assessment in real-world industrial settings⁷. Heart rate variability (HRV) and electrodermal activity (EDA) index autonomic regulation and sympathetic arousal⁸ and electroencephalography (EEG) offers markers of attention and cognitive control⁹. Together, these measures support operator-aware multimodal assessment in HRC.

Detecting stress and workload in HRC requires being sensitive to physiological changes yet robust in real-world settings. Multimodal sensing outperforms single-signal approaches by combining complementary channels¹⁰. Advanced fusion methods, including deep learning, have shown high sensitivity to acute stress. However, their robustness often degrades in industrial environments due to artefacts, sensor variability, and uncertain labels¹¹. Consequently, interpretable rule-based or hybrid pipelines that integrate physiological features with contextual information offer a more practical alternative¹².

This study introduces a controlled HRC (Figure 1) paradigm that combines laboratory rigour with real-world applicability. Synchronised EEG, HRV, EDA, and video data were collected across baseline and repeated cobot-assisted tasks to support both interpretable features analysis and benchmarking of fusion models, providing a foundation for adaptive Industry 5.0 collaboration.

⁴Seemal Asif et al., “Exploring Tasks and Challenges in Human-Robot Collaborative Systems: A Review,” *Robotics and Computer-Integrated Manufacturing* 97 (1 February 2026): 103102. <https://doi.org/10.1016/J.RCIM.2025.103102>

⁵Claudio Urrea and John Kern, “Recent Advances and Challenges in Industrial Robotics: A Systematic Review of Technological Trends and Emerging Applications,” *Processes* 13, no. 3 (12 March 2025): 832. <https://doi.org/10.3390/PR13030832>

⁶Green et al., “Human-Robot Collaboration: A Literature Review and Augmented Reality Approach in Design,” 1–18.

⁷Andrew Weightman et al., “Key Fundamentals and Examples of Sensors for Human Health: Wearable, Non-Continuous, and Non-Contact Monitoring Devices,” *Sensors* 25, no. 2 (19 January 2025): 556. <https://doi.org/10.3390/S25020556>.

⁸Hugo F. Posada-Quintero et al., “Elevation of Spectral Components of Electrodermal Activity Precedes Central Nervous System Oxygen Toxicity Symptoms in Divers,” *Communications Medicine* 4, no. 1 (1 December 2024): 1–11. <https://doi.org/10.1038/s43856-024-00688-4>

⁹Johnny V. V. Parr, Germano Gallicchio, and Greg Wood, “EEG Correlates of Verbal and Conscious Processing of Motor Control in Sport and Human Movement: A Systematic Review,” *International Review of Sport and Exercise Psychology* 16, no. 1 (31 December 2023): 396–427. <https://doi.org/10.1080/1750984X.2021.1878548>

¹⁰Jing Zhang et al., “Real-Time Mental Stress Detection Using Multimodality Expressions with a Deep Learning Framework,” *Frontiers in Neuroscience* 16 (5 August 2022): 947168. <https://doi.org/10.3389/fnins.2022.947168>

¹¹Gulin Dogan and Fatma Patlar Akbulut, “Multi-Modal Fusion Learning through Biosignal, Audio, and Visual Content for Detection of Mental Stress,” *Neural Computing and Applications* 35, no. 34 (1 December 2023): 24435–54. <https://doi.org/10.1007/s00521-023-09036-4>

¹²“Autonomic Arousal in Social Anxiety: An Electrodermal Activity Study During an Emotionally Salient Cognitive Task,” accessed 11 September 2025. <https://arxiv.org/html/2507.15871v1>

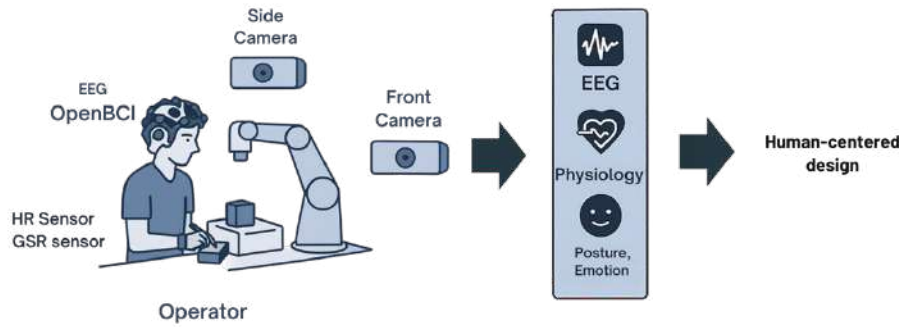


Figure 1: Experimental Setup for HRC Assembly.

Methods

Participants and Setting

The study was conducted at the FrED Factory Lab (25 °C, 102 kPa). Five engineering undergraduates (19-21 years; four male, one female; right-handed) participated. Three had prior cobot exposure. None reported neurological or cardiovascular disorders or medication affecting automatic function. Informed consent was obtained.

Experimental Protocol

Participants completed two seated baselines (90 s each): eyes open and eyes closed. They then performed six consecutive cobot-assisted assembly trials (~35 min total). An xArm 6 XI1202 delivered an Arduino Uno board; participants connected 14 jumper wires following visual instructions and signalled completion for retrieval. The full session lasted ~1 hour (Figure 2).

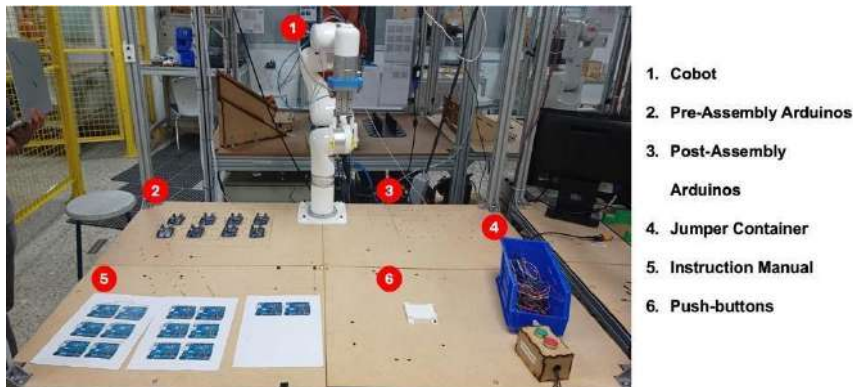


Figure 2: Overview of the workstation.

Data Acquisition

EEG was recorded using an OpenBCI Ultracortex Mark IV (8 dry electrodes: FP1, FP2, C3, C4, P3, P4, T5, T6). Cardiac activity was captured via Polar H10 (HR at 1 Hz). EDA was measured with a Grove GSR sensor (~5.5 Hz) embedded in open-finger gloves and streamed via an ESP32. Two synchronised video streams (frontal and lateral) supported behavioural and ergonomic analysis. All modalities were time-synchronised and stored for offline analysis (Figure 3).

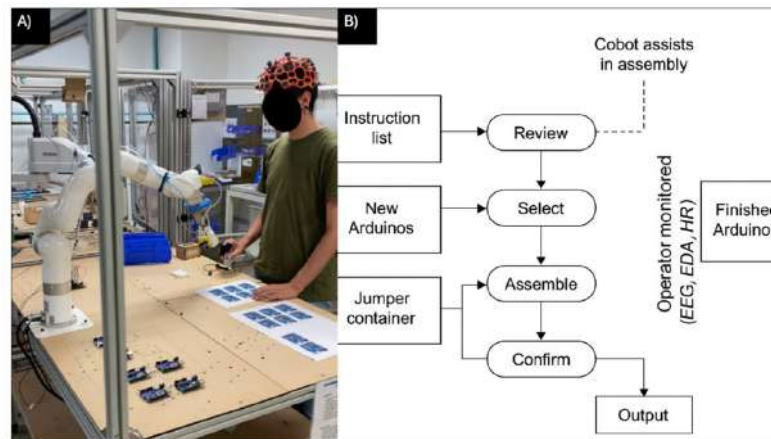


Figure 3: Experimental execution in the non-adaptive condition: (a) participant and (b) workload.

Analysis

EDA was decomposed into tonic and phasic components, with features including SCR peaks/min and band power. Cardiac metrics included mean HR, RMSSD, and frequency-domain LF/HF components. Ergonomic analysis extracted joint angles (shoulder, elbow, wrist, neck, trunk) and time spent in low-, medium-, and high-risk postural bands.

Results

Electrodermal Activity

Relative to the eyes-open baseline, eyes-closed relaxation reduced SCRs modestly (-11%). During HRC, SCRs decreased substantially (-42%), while tonic EDA increased progressively from baseline to eyes closed (+40%) and peaked during HRC (+239%). Phasic power increased slightly during eyes-closed relaxation (+12%) but decreased during HRC (-17%), indicating a shift from transient reactivity to sustained sympathetic activation. Figure 4 presents the 3D GSR spectrograms across conditions for a representative participant.

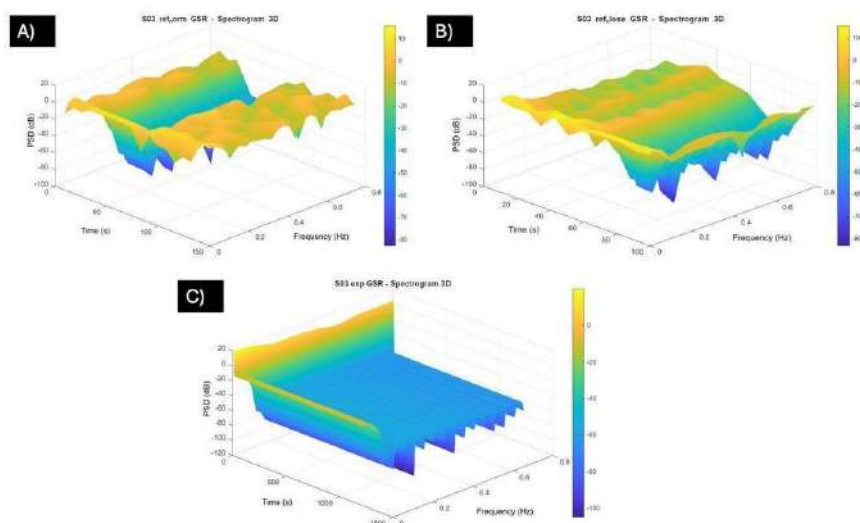


Figure 4: Subject 3: A) eyes open, B) eyes closed, C) experience. 3D spectrograms showing the power spectral density (PSD).

Figure 5 shows the distribution of skin conductance responses (SCRs) per minute across eyes-open, experimental, and eyes-closed conditions.

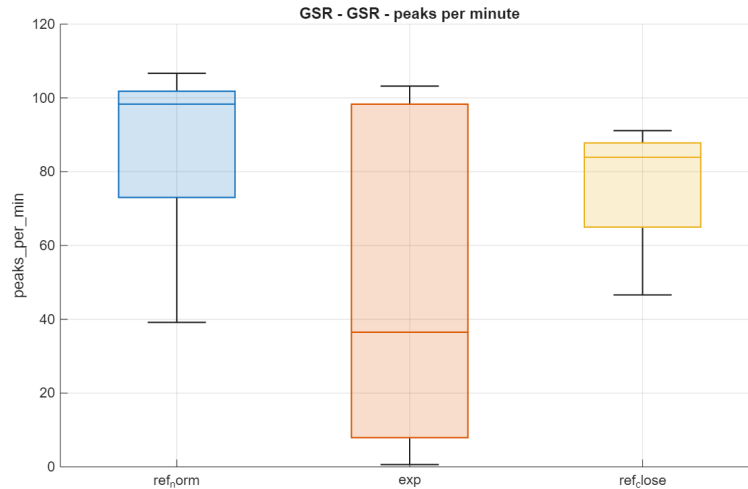


Figure 5: Box plot of GSR peaks per minute.

Figure 6 shows changes in tonic and phasic GSR components across conditions. Tonic activity was low at the eyes-open baseline, increased during eyes-closed rest (+40%), and rose markedly during the HRC task (+239%).

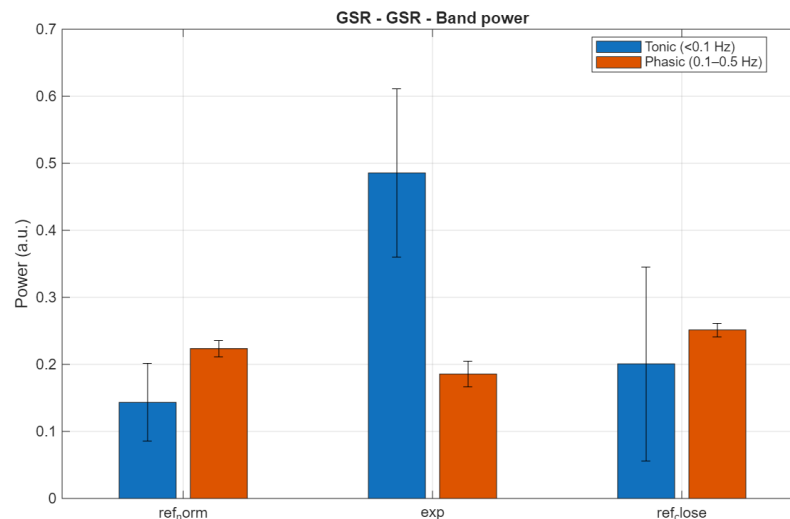


Figure 6: Box plots of GSR band power.

Table 1 summarises GSR features across conditions. SCRs decreased from baseline to the HRC task, while tonic power increased and phasic power declined, indicating sustained sympathetic activation.

Table 1: GSR metrics by condition.

Metric	Ref (eyes open)	Ref (eyes closed)	Experimental
Peaks per min (GSR)	85.73 ± 27.29	76.39 ± 20.16	49.46 ± 47.97
Tonic power	0.14 ± 0.13	0.20 ± 0.29	0.49 ± 0.28
Phasic power	0.22 ± 0.03	0.25 ± 0.02	0.19 ± 0.04
Min	-1.38 ± 0.45	-1.38 ± 0.37	-1.06 ± 1.11
Max	1.64 ± 0.20	1.55 ± 0.12	5.22 ± 7.43

Cardiac Measures

Mean HR remained stable at baseline (~77 bpm), increased slightly during eyes-closed relaxation (+3%), and rose during HRC (+12%). RMSSD decreased during HRC, indicating reduced parasympathetic modulation. Frequency-domain analysis showed increases in both LF (+28%) and HF (+26%) during HRC, with a higher LF/HF ratio consistent with sympathetic predominance. Figure 7 compares the distribution of average cardiac activity across the same three conditions (*ref_norm*, *exp*, and *ref_close*).

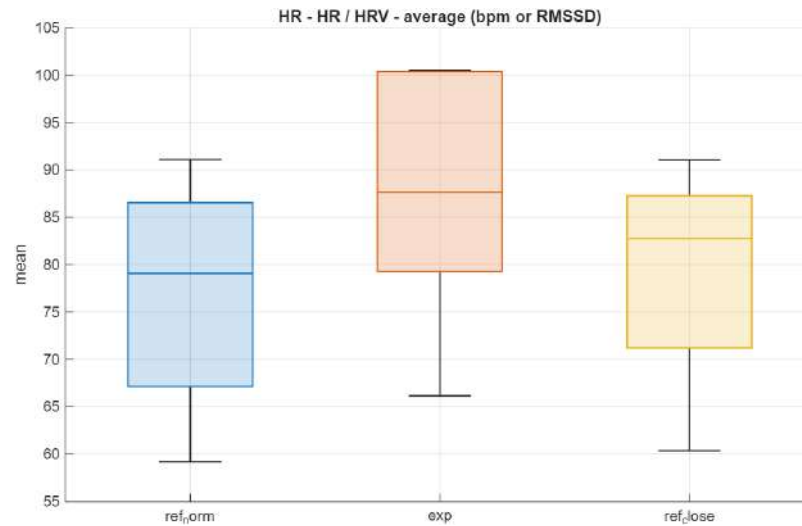


Figure 7: Box plot of HR/HRV average.

Figure 8 shows increased LF and HF power with a higher LF/HF ratio during HRC, indicating sympathetic dominance.

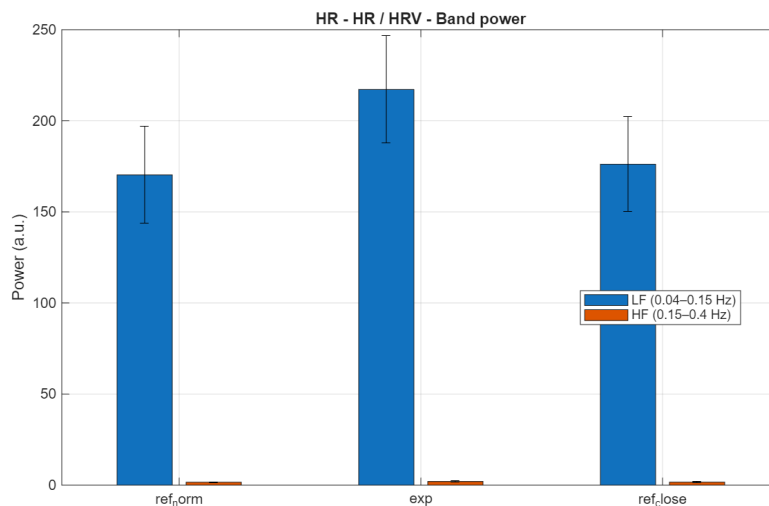


Figure 8: Box plots of HR/HRV band power.

Table 2 summarises cardiac indices across conditions. Mean HR and LF/HF increased during HRC, indicating sympathetic predominance, whereas the eyes-closed baseline showed a more balanced autonomic profile.

Table 2: HR / HRV metrics.

Metric	Ref (eyes open)	Ref (eyes closed)	Experimental
Mean	76.84 ± 12.60	79.24 ± 13.18	87.65 ± 14.17
SD	3.41 ± 2.35	2.76 ± 0.80	3.81 ± 0.97
Tonic power	170.29 ± 59.43	176.14 ± 52.09	217.18 ± 65.77
Phasic power	1.61 ± 0.56	1.66 ± 0.52	2.03 ± 0.64

Ergonomic Assessment

Most joints operated within low-risk ranges. Shoulder elevation and trunk flexion remained low and stable; elbow flexion showed moderate variability. Wrist flexion exhibited frequent deviations, and neck flexion consistently occupied high-risk bands, identifying primary ergonomic concerns during the task. Figure 9 shows the frontal and lateral views of the operator while performing an assembly task with a cobot.

**Figure 9:** Ergonomic analysis of the operator.

Figure 10 illustrates the distribution of joint angles recorded during the task.

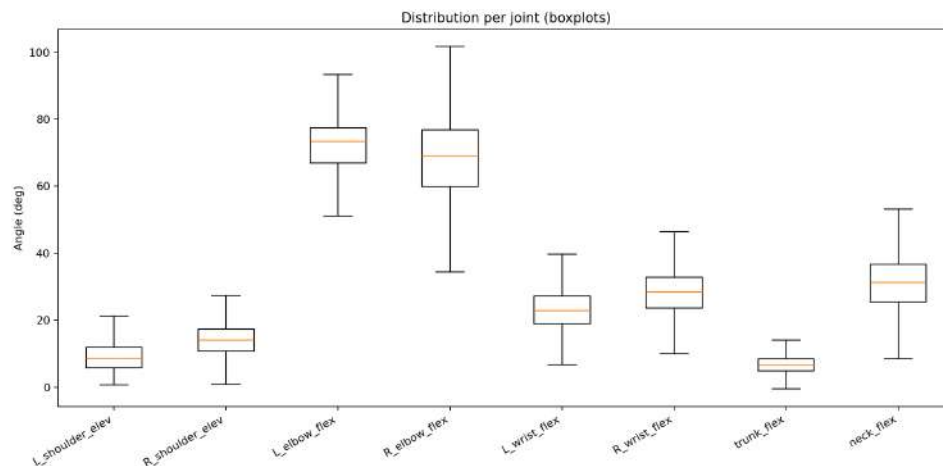
**Figure 10:** Distribution per joint: shoulders, elbows, wrists, trunk, and neck.

Figure 11 highlights neck and wrist postures as the main ergonomic risk factors during the task.

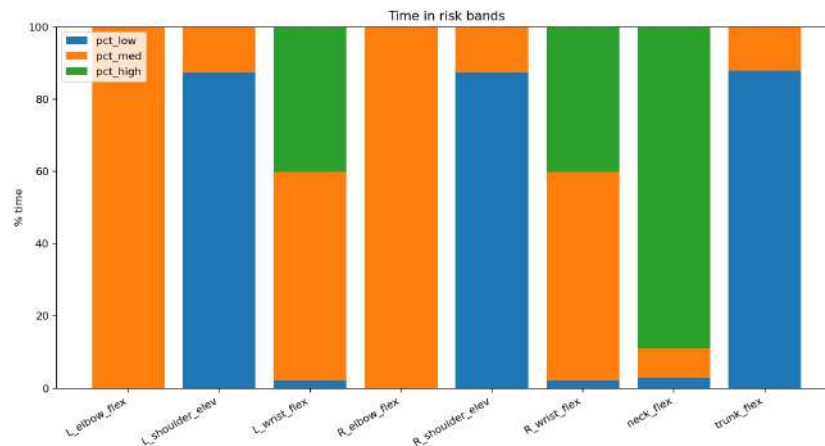


Figure 11: Percentage of task duration for each joint.

Discussion

This study shows that repetitive HRC elicits stress- and fatigue-related psychophysiological signatures, characterised by reduced phasic EDA (-42%) and elevated tonic activation ($+239\%$), indicating sustained sympathetic arousal, a pattern commonly linked to cumulative stress and mental fatigue^{13 14}. Together, these findings indicate that even predictable cobot-assisted tasks impose a measurable physiological load on operators.

These results align with prior work showing that physiological stress markers can emerge without conscious awareness, as demonstrated by rule-based GSR approaches¹⁵, and with studies highlighting the effectiveness of multimodal biosensing for stress detection¹⁶. While deep-learning approaches emphasise classification accuracy, the present study prioritises interpretable physiological markers to better characterise the operator stage during HRC.

Ergonomic analysis identified neck flexion and wrist deviation as primary risk factors, consistent with links between sustained postures, autonomic stress, and altered HRV¹⁷. This convergence suggests a dual risk of physical strain and stress during HRC tasks.

Conclusions and Future Work

This study establishes a concise multimodal baseline for assessing stress, fatigue, and ergonomic risk in HRC, aligned with Industry 5.0 principles. HRC tasks elicited sustained sympathetic activation relative

¹³Kalliopi Kyriakou et al., “Detecting moments of stress from measurements of wearable physiological sensors,” *Sensors*, 19, no. 17 (2019): 3805. 10.3390/s19173805

¹⁴Hugo F. Posada-Quintero et al., “Elevation of spectral components of electrodermal activity precedes central nervous system oxygen toxicity symptoms in divers,” *Communications Medicine* 4, no. 1 (2024): 1–11. 10.1038/s43856-024-00688-4

¹⁵Kalliopi Kyriakou et al., “Detecting moments of stress from measurements of wearable physiological sensors,” 3805.

¹⁶Jing Zhang et al., “Real-time mental stress detection using multimodality expressions with a deep learning framework,” *Frontiers in Neuroscience*, 16, (2022): 947168. 10.3389/fnins.2022.947168

¹⁷Jeremy J. Peabody et al., “A systematic review of heart rate variability as a measure of stress in medical professionals,” *Cureus* 15, no. 1 (2023). 10.7759/cureus.34345

to baseline, while ergonomic analysis highlighted risks to the neck and wrist. These insights support adaptive cobot strategies that adjust behaviour based on operator state, potentially improving safety, performance, and well-being. Future work will integrate real-time EEG features and adaptive control to personalise collaboration.

Acknowledgements

The authors acknowledge the FrED Factory Lab at Tecnológico de Monterrey and thank Dr. Manuel Cebal, Dr. Mauricio Ramirez, and Iñaki García Bárcena García for their support.

Supplementary Information

Ethics and Consent: Ethical approval was waived due to the absence of identifiable data. Informed consent was obtained from all participants.

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Chapter 21

Digital Twins of the Retina: A Computational Framework for Personalised Microvascular Health Assessment

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Abstract

Digital twins of the retina have the potential to personalise treatment options for individuals. This study presents a computational framework for generating digital twins of retinal vasculatures, simulating haemodynamics and transit times, on an individual basis. Starting with optical coherence tomography angiography (OCTA) and fundus photographs, we developed a pipeline to segment the retinal vasculature, virtually recreate it and run blood flow simulations tailored to each individual.

Digital twins of six eyes were created, and blood flow was solved through the networks, demonstrating variability between individuals. Simulations were validated against literature data for blood flow and blood velocity distributions. Diseases such as diabetic retinopathy and retinal vein occlusion were simulated for each case, demonstrating variable risk between individuals.

Our framework enables computation of microvascular haemodynamic metrics that are challenging to measure directly. In particular, mean transit times and transit time heterogeneity—important markers of microvascular health in other organs—were derived from the digital twins. This proof-of-concept demonstrates the potential of computational frameworks as tools to explore associations between microvascular ageing, disease, and retinal health. Future integration with real-time imaging devices could allow live-streamed feedback and personalised risk prediction, strengthening the translational impact of this approach.

Keywords: *Retinal Digital Twins, Haemodynamic Simulations, Diabetic Retinopathy, Retinal Biomarkers, Personalised Healthcare*

Introduction

The retina is one of the few places in the human body where the microvasculature can be visualised non-invasively. Retinal health reflects not only ocular function but also systemic vascular conditions, including diabetes, hypertension, and neurodegenerative disorders¹. Early detection and monitoring of microvascular changes can provide valuable insights for preventing vision loss and assessing overall cardiovascular risk.

¹J. Chua et al., “Optical coherence tomography angiography of the retina and choroid in systemic diseases.” *Progress in Retinal and Eye Research*, 103 (November 2024): 101292.

However, current clinical assessments rely largely on qualitative grading or global averages, overlooking inter-individual variability in microvascular topology and function.

Digital twins (virtual replicas of biological systems) are gaining traction across medicine. In cardiology, orthopaedics, and oncology, digital twins have been used to simulate organ function, predict disease progression, and optimise therapies^{2,3,4}. Yet their application in ophthalmology is still in its infancy^{5,6,7}. We hypothesised that creating digital twins of the retina could capture individual-specific vascular structures and haemodynamic patterns, providing a foundation for personalised diagnostics and treatments.

This chapter presents an image-based computational framework for constructing retinal digital twins from optical coherence tomography angiography (OCTA) and fundus images. By modelling blood flow and red blood cell movements, we aimed to (i) demonstrate variability across individuals, (ii) validate simulations against existing literature, (iii) explore disease conditions such as diabetic retinopathy, and (iv) investigate microvascular health markers, particularly mean transit time and heterogeneity.

Methods

Generating the Retinal Digital Twins

Six individuals were chosen: 4 from the open-source DRIVE dataset⁸ and 2 from an in-house dataset⁹. These images were a combination of colour fundus photographs and optical coherence tomography (OCT), augmented with en-face OCTA. The vessel networks were segmented from these images, with Voronoi tessellations representing the three-layered capillary bed connected.

For each individual, 20 capillary beds were generated due to the inability to visualise them in the imaging; thus, each individual had 20 twins with the same retinal morphology, except for the central capillary beds. The segmentation process is visualised in Figure 1.

²J. Corral-Acero et al., “The ‘Digital Twin’ to enable the vision of precision cardiology.” *European Heart Journal* 41 no. 48 (December 2020): 4556–64.

³M.C. Dean et al., “Leveraging digital twins for improved orthopaedic evaluation and treatment.” *Journal of Experimental Orthopaedics* 11 no. 4 (November 2024): e70084.

⁴U.S. Asghar and C. Chung, “Application of digital twins for personalized oncology.” *Nature Reviews. Cancer* 25 no. 11 (November 2025): 823–25.

⁵R.J. Hernandez et al., “Advancing Treatment of Retinal Disease through in Silico Trials.” *Progress in Biomedical Engineering (Bristol, England)* 5 no. 2 (2023): 22002.

⁶R.J. Hernandez et al., “Linking Vascular Structure and Function: Image-Based Virtual Populations of the Retina.” *Investigative Ophthalmology and Visual Science* 65 no. 4 (April 2024): 40.

⁷E. Brown et al., “Physics-Informed Deep Generative Learning for Quantitative Assessment of the Retina,” *Nature Communications* 15 no. 1 (2024).

⁸J. Staal et al., “Ridge-based vessel segmentation in color images of the retina.” *IEEE Transactions on Medical Imaging* 23 no. 4 (April 2004): 501–09.

⁹R.J. Hernandez et al., “AI and the Eye – Integrating Deep Learning and in Silico Simulations to Optimise Diagnosis and Treatment of Wet Macular Degeneration,” *medRxiv* (2024).

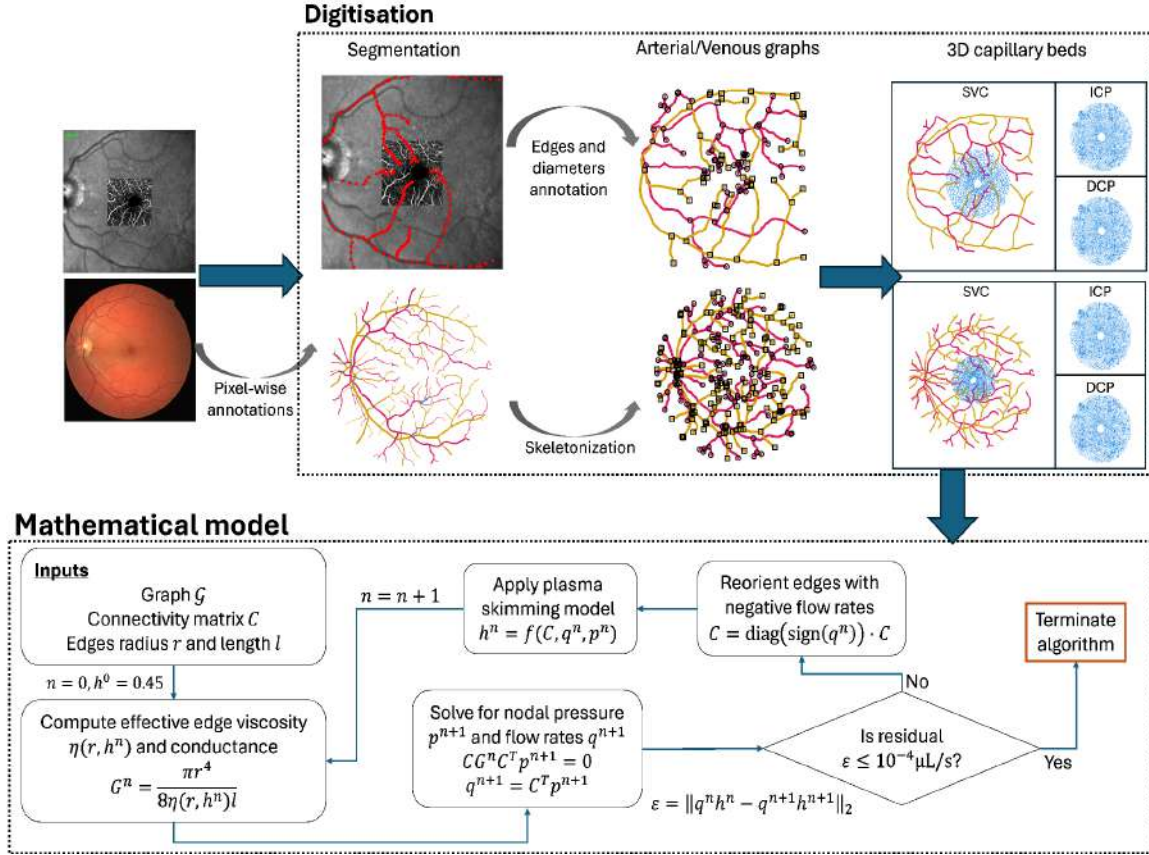


Figure 1: Summary of the framework to create digital twins, including the plasma skimming and blood flow model.

Simulating Blood Flow

The model assumes Poiseuille flow:

$$\Delta p = \frac{8\eta(r, h)Lq}{\pi r^4}$$

where q is the volumetric blood flow, r and L the vessel radius and length, and Δp the pressure drop between the ends of the vessel. The use of an effective viscosity term $\eta(r, h)$ as a function of vessel radius and discharge haematocrit (h) accounts for the non-Newtonian behaviour of blood and the Fåhræus-Lindqvist effect. A plasma skimming model, to simulate the uneven distribution of red blood cells at bifurcations in the network, is also introduced. The blood flow algorithm is shown in Figure 1.

Results

Digital Twins of Health Eyes

Six digital twins of healthy eyes were developed, as shown in Figure 2. Total retinal blood flow through the eyes was $43.28 \pm 12.19 \mu\text{L/min}$, similar to what has been measured *in vivo* in the retina ($30 - 50 \mu\text{L/min}$)¹⁰. Transit times of red blood cells were also computed, with mean transit times (MTT) across

¹⁰V. Doblhoff-Dier et al., "Measurement of the total retinal blood flow using dual beam Fourier-domain Doppler optical coherence tomography with orthogonal detection planes," *Biomedical Optics Express* 5 no. 2 (January 2014): 630–42.

the 6 twins ranging from 4.8 s to 9.9 s, which compare well with the measured MTT of $4.9 \pm 1.9 \text{ s}^{11}$. As such, we validate the blood flow through the digital twins.

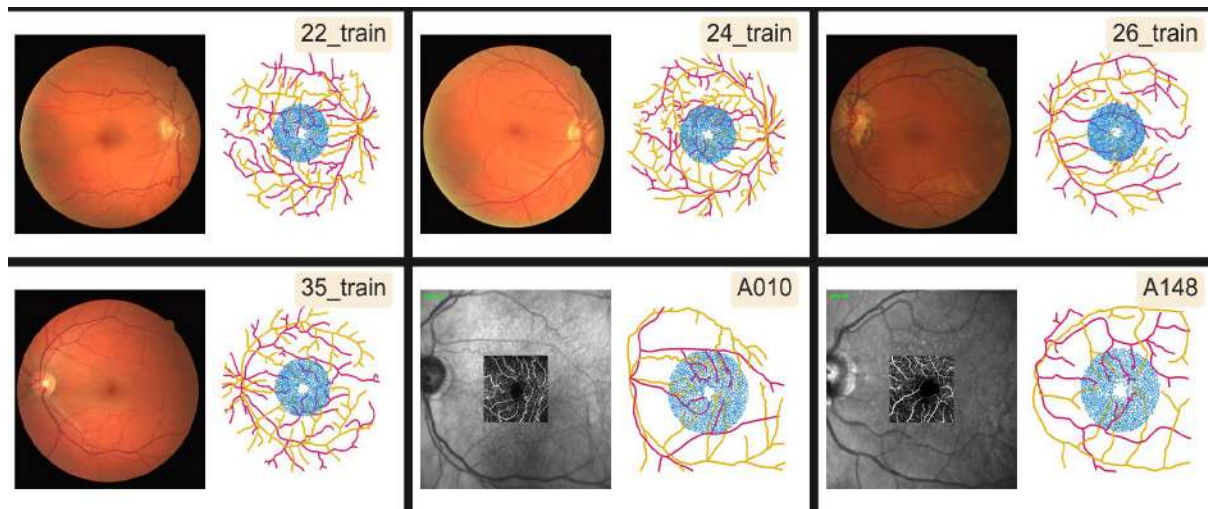


Figure 2: Example of 6 generated digital twins. The graph of the vasculature is shown next to the generated vascular graph. Arteries (in red) and veins (in orange) are digitised from the segmentation. Capillaries (in blue) are randomly generated with Voronoi tessellation.

Diabetic Retinopathy and *in silico* Biomarkers

Diabetic retinopathy affects the blood vessels of the retina. One aspect of this disease is capillary rarefaction. As such, we implemented a diabetic retinopathy model to simulate the advancement of diabetic symptoms through random capillary removal. We simulate an intermediate case by removing 2% of vessels and an advanced case by removing 5% of vessels. An example of blood pressure maps for one individual at different stages of the disease is shown in Figure 3.

Discussion

We also sought to discover whether mean transit time (MTT) and capillary transit time heterogeneity (CTH) could be used as *in silico* biomarkers of different stages of disease. As shown in Figure 4, there is a clear shift in each individual towards longer MTT and CTH as the disease progresses, suggesting its potential for early detection of diabetic retinopathy.

Personalised Retinal Healthcare

Our findings highlight the potential of retinal digital twins to inform personalised approaches in ophthalmology. By capturing patient-specific vascular structures and haemodynamics, digital twins go beyond population-based averages and open avenues for risk stratification tailored to individuals. In particular, physics-informed simulations of blood flow, and potentially oxygen transport, can provide further insight into disease impact for individuals and can help tailor personalised treatment.

¹¹G. Bjärnhal et al., “Analysis of mean retinal transit time from fluorescein angiography in human eyes: Normal values and reproducibility,” *Acta Ophthalmologica Scandinavica* 80 no. 6 (December 2002): 652–55.

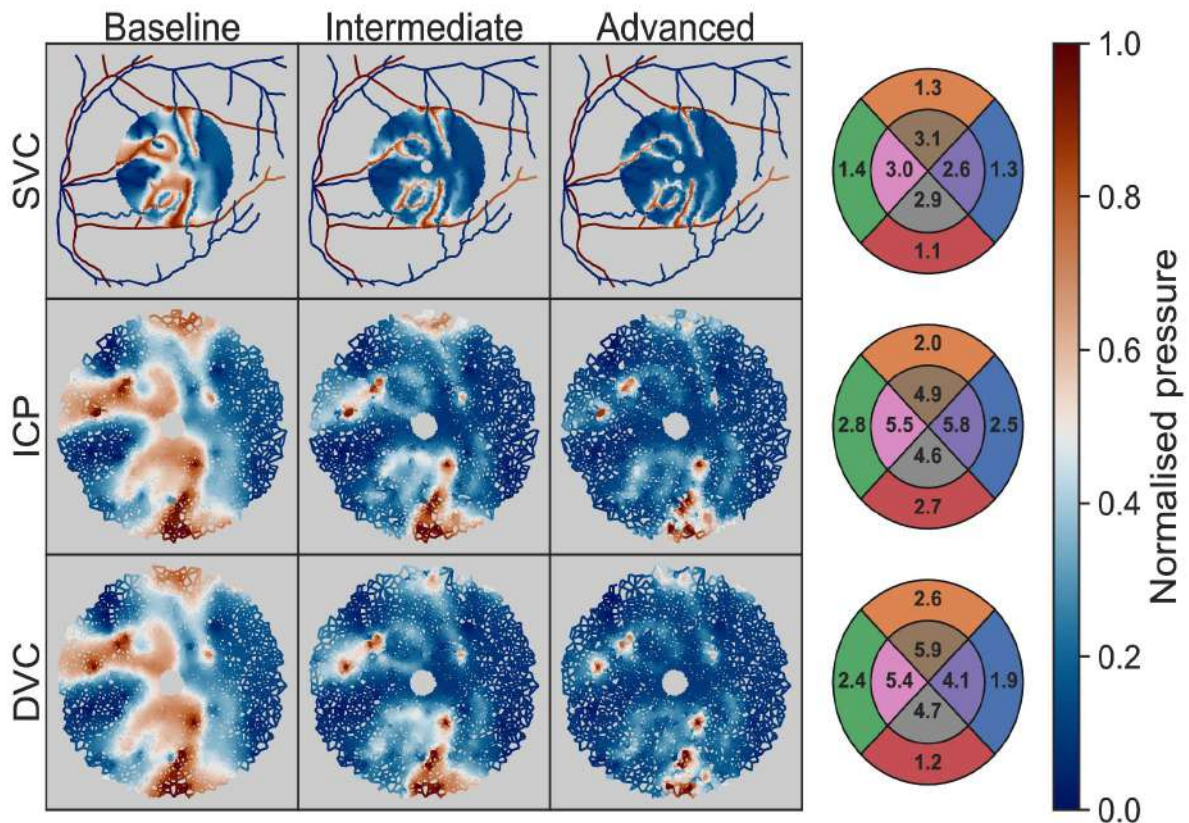


Figure 3: Blood pressure changes with diabetes in one digital twin. From left to right, capillary rarefaction increases from the baseline conditions to the advanced stages. Pie charts show the percentage of lost capillary area between healthy and intermediate diabetic stages (outer ring) and between the healthy and advanced diabetic stages (inner ring).

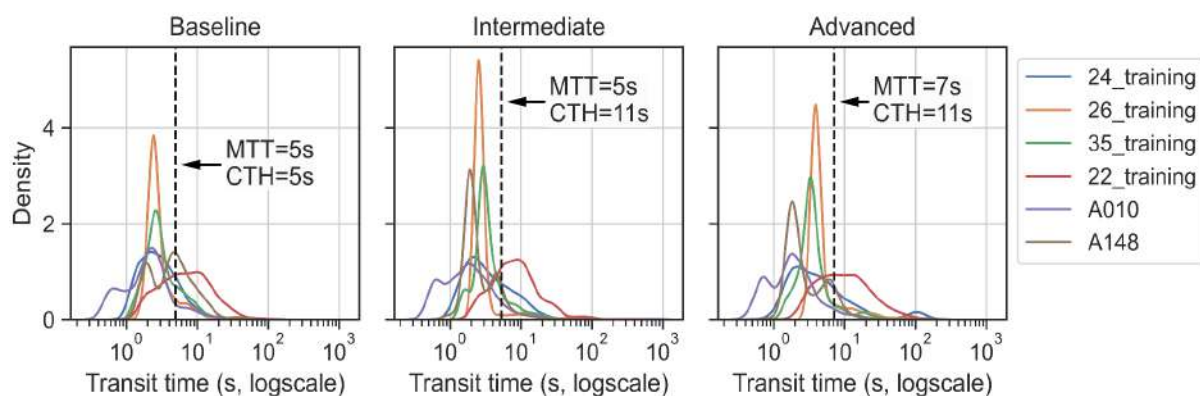


Figure 4: Plot of the probability density functions of transit times with the advancement of diabetic symptoms. Each line corresponds to a single digital twin. The vertical dashed line shows the means of MTT and CTH among the six individuals plotted.

Clinical Implications

MTT and CTH are established markers of pathology in cerebral and cardiovascular research¹². We have demonstrated the potential of these markers to detect disease *in silico*, potentially extending their use in ophthalmology as indicators of retinal microvascular health. If validated in larger cohorts, these

¹²L. Østergaard, "Blood Flow, Capillary Transit Times, and Tissue Oxygenation: The Centennial of Capillary Recruitment." *Journal of Applied Physiology* 129 no. 6 (2020): 1413–21.s

metrics could provide early warning signals for diseases such as diabetic retinopathy or glaucoma, enabling pre-emptive interventions.

Translational Potential

One of the strengths of this framework is its compatibility with existing imaging modalities. OCTA and fundus photography are already widely available in clinical settings. Integrating our pipeline with these devices could enable near real-time generation of digital twins. This would provide clinicians with immediate haemodynamic insights, including MTT and CTH biomarkers, alongside routine imaging.

‘Real-time’ Retinal Digital Twins

The proper definition of an engineering digital twin includes a real-time stream of information from the real world to the virtual one, which the digital twin can update. In medicine, due to the fundamental constraints of real-time monitoring of patients, it has not been feasible to provide that live stream of information to the digital twin. However, the retina, of all the organs, is arguably one of the easiest to image, allowing for repeat scans to be taken with enough frequency to allow for a longitudinal digital twin to be built up. We are currently working towards this through our study at the St Paul’s Eye Centre, Liverpool, where we are collecting repeat scans of patients over 3 years. This will eventually allow us to build a longitudinal digital twin, which, if integrated into imaging platforms, would provide instant feedback, enabling ophthalmologists to explore disease trajectories virtually.

Limitations

This proof-of-concept is limited by a small sample size and simplified boundary conditions. Disease models, such as that for diabetic retinopathy, remain stylised and do not account for biochemical processes such as angiogenesis or vessel remodelling. Moreover, direct in vivo flow validation was unavailable for individuals in our dataset (validation was done at the population level). Larger studies with multimodal validation are required.

Conclusions

We presented a computational framework to generate digital twins of the retinal vasculature from OCTA and fundus images. The model reproduced literature-consistent haemodynamics, revealed inter-individual variability, and simulated disease scenarios with personalised outcomes. Importantly, it enabled the derivation of perfusion markers such as MTT and CTH, which may serve as new retinal biomarkers of microvascular health.

Digital twins represent a promising tool for personalised ophthalmology, bridging imaging data with computational modelling. Future work will focus on real-time device integration, scaling to larger cohorts, and linking retinal twins to systemic models of ageing and disease

Acknowledgements

RJH is funded by an EPSRC Doctoral Network in AI & Future Digital Health studentship.

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Chapter 22

The Internet of Beings: The Nightmares and Dreams of Digitalising Human Bodies

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Abstract

Internet of Beings is a voyage inside what the author predicts to be the third and final phase of the Internet revolution. The first phase ('Internet of Computers') linked all digital devices into a seamless information system; the second, 'Internet of Things', is integrating physical objects into such a network. The third is where living bodies ('beings') and learning machines will be connected among themselves through increasingly powerful, smaller devices. This chapter captures some of the main results of a vast interdisciplinary research and management consulting practice that the author has conducted in the last few years. The book will provide the big picture of a transformation: the underlying epistemological belief is that an understanding of such large technological, scientific, and economic change requires a frame that connects its different dimensions.

Keywords: *Artificial Intelligence, Internet, Healthcare, Pharmaceutical, Insurance*

Introduction – The Paradigm

The convergence between computer science and healthcare¹, data and drug discovery, may be the real next big thing. It may become the most important achievement of the Internet revolution. The 'internet of beings' can provide the theoretical framework to make sense of it. The paradigm is about a vision in which living bodies and computers become connected into a potentially seamless, global information system^{2,3}.

This vision is made more likely by the convergence of three powerful trends.

First, the huge investments made by tech companies have been in so-called 'artificial intelligence'. The objective of defeating some of the diseases we have accepted as part of our existence may give AI a problem to solve with the new technology and a possible return on such an investment. Second, the crisis of Western healthcare sectors is a political problem for most governments, together with the

¹Julia Amann et al., "Explainability for Artificial Intelligence in Healthcare: A Multidisciplinary Perspective," *BMC Medical Informatics and Decision Making* 20, no. 1 (November 30, 2020).

²Ernesto De la Paz et al., "A Self-Powered Ingestible Wireless Biosensing System for Real-Time in Situ Monitoring of Gastrointestinal Tract Metabolites," *Nature Communications* 13, no. 1 (December 1, 2022): 7405, <https://doi.org/10.1038/s41467-022-35074-y>.

³The Economist, "Wearable Technology Promises to Revolutionise Health Care," *The Economist*, May 5, 2022, <https://www.economist.com/leaders/2022/05/05/wearable-technology-promises-to-revolutionise-health-care>.

possibility for emerging countries to leapfrog the West. Third, the legacy of COVID-19, which introduced technologies in the delivery of health (and education) to nearly all families^{4,5}.

The work is exploring the opportunities of such an evolution^{6,7}; the industrial policies that may create national competitive advantages around the paradigm; the risks that may dwarf the ones we are currently trying to tame (body hacking may become a possibility); the regulations that national and global policymakers will design to limit those risks.

The Technological Implications

It is an evolution that has been anticipated by wearable sensors (like the ones that Apple and Garmin are perfecting) and implanted machines (like the cardiac bypasses) that have been around for years^{8,9}. Yet these devices are about to become capable of performing increasingly sophisticated functions that the book is exploring¹⁰.

This evolution will be accelerated by three simultaneous technological developments. The rise of large language models: this may lift the limits of machines' ability to make sense of data, which is dirty because it uses semantics that were not recognisable by computers. The introduction of communication systems (so-called 6G) is essential for remotely intervening in organisms under certain conditions. The development of chips and quantum computers¹¹ that will ultimately be able to provide the possibility to process much larger datasets.

The Impact on Industries: Five Industries at a Strategic Crossroad

The transformation in how we protect health will affect a wide variety of industries.

We will, more specifically, focus on three: insurance, pharma¹², and high tech.

⁴George Abi Younes et al., "COVID-19: Insights from Innovation Economists," *Science & Public Policy* 47, no. 5 (July 1, 2020), <https://doi.org/10.1093/scipol/scaa028>.

⁵Maria Costanza Cau and Giuseppe Cipolletta, "The Covid19 Pandemic: Winners and Losers - Vision | Think Tank; a 'Factory of Ideas,'" Thinktank.vision, February 25, 2021, <https://www.thinktank.vision/en/publications/the-covid19-pandemic-winners-and-losers?highlight=WYJb3ZpZDE5Il0=>.

⁶Erica Coe et al., "Adding Years to Life and Life to Years," McKinsey & Company, <https://www.mckinsey.com/mhi/our-insights/adding-years-to-life-and-life-to-years>.

⁷"Closing in on Cancer," *The Economist*, September 16, 2017, <https://www.economist.com/leaders/2017/09/16/closing-in-on-cancer>.

⁸Andrea M. Matwyshyn, "The Internet of Bodies," *William & Mary Law Review* 61, no. 1 (October 2019), <https://scholarship.law.wm.edu/wmlr/vol61/iss1/3/>.

⁹"The Quantified Self," *The Economist*, 2022, <https://www.economist.com/technology-quarterly/2022-05-07>.

¹⁰"Wearable Tech to Become \$232 Billion Industry by 2030, Forecasts GlobalData," GlobalData, February 9, 2026, <https://www.globaldata.com/media/strategic-intelligence/wearable-tech-to-become-232-billion-industry-by-2030-forecasts-globaldata/>.

¹¹David P. DiVincenzo, "The Physical Implementation of Quantum Computation," *Fortschritte Der Physik - Progress of Physics* 48 (October 25, 2000): 771–83, [https://doi.org/10.1002/1521-3978\(200009\)48:9/11%3C771::AID-PROP771%3E3.0.CO;2-E](https://doi.org/10.1002/1521-3978(200009)48:9/11%3C771::AID-PROP771%3E3.0.CO;2-E).

¹²Marc Mitchell and Lena Kan, "Digital Technology and the Future of Health Systems," *Health Systems and Reform* 5, no. 2 (2019): 113–20, <https://doi.org/10.1080/23288604.2019.1583040>.

This will, indeed, be a transformation where it is not necessarily true that in the process the ‘first will win all’ (though in some industries this may happen) or that it would be better for companies to adopt disruption as soon as possible: innovation will carry not only the risk of failure but also of cannibalising existing competitive advantages, operations, customer bases, and branding. This is especially true for insurance that will be faced by a transformation that may change the nature itself of their industry (personalisation of the risk is somehow the opposite of managing risks by pooling them together); and pharma (enhancing drug discovery with much vaster databases may change the economics of research and the definition itself of intellectual property).

The ‘internet of beings’ will also be a huge opportunity/challenge for the Internet giants: companies like Alphabet have already made significant investments into healthcare and pharma as a possible diversification of a business model entirely based on revenues from digital marketing. So far, these efforts have not been successful (as the cases of Alphabet’s ventures, such as Calico and Verily Life Sciences, seem to demonstrate): Silicon Valley has so far had tough times when dealing with the production of socially relevant, highly regulated goods. And yet, as mentioned, the rise of artificial intelligence makes it more urgent for Internet companies to find new revenue streams to repay their huge investments into AI.

It would, however, be naïve to take for granted that economic change will proceed at the same pace as the evolution of technologies. The last few decades have shown clearly how resistance to change¹³ can delay or derail transformation. This is especially true (as we anticipated in chapter one) when it comes to healthcare, which has been traditionally reluctant to embrace digital innovation. The book will explore such resistance.

Social Implications: The Clash Between Two Opposite Visions

The idea of ‘digitalising human bodies’ will pose entire societies at a crossroads. More specifically, two opposite outcomes are theoretically possible as far as equality within countries and across them¹⁴.

Personalised insurance may, for instance, push all insurance companies to compete for the same, healthier individuals (leaving everybody else paying higher premiums); similarly, the personalisation of drugs (and the multiplication of drug products) may also have a devastating impact on cost and, thus, prices.

And yet it is also possible that the opposite scenario, where drugs will cost much less because they use personal information that belongs to patients and individuals, which will have to be rewarded for sharing data. Constant monitoring may also have the effect of allowing much better prevention, which would make healthcare more efficient and less costly.

¹³William J Baumol and David M De, *The Cost Disease: Why Computers Get Cheaper and Health Care Doesn’t* (New Haven, Conn.; London: Yale University Press, 2012), 3–32.

¹⁴N M Hjelm, “Benefits and Drawbacks of Telemedicine,” *Journal of Telemedicine and Telecare* 11, no. 2 (2005): 60–70, <https://doi.org/10.1258/1357633053499886>.

It is possible, indeed, both a dystopic scenario¹⁵ as the one envisaged by some Silicon Valley tycoons, where some superhumans could eventually live forever. And one where the use of technologies will serve the more mundane and concrete policy target of making health accessible to everybody. The direction we will undertake heavily relies on the capability of policymakers to foresee the transformation and steer it towards reasonable goals.

The Consequences on Geopolitics and Global Competitiveness

The digitalisation of health and drug discovery will elicit different responses: some countries, most likely the developed liberal democracies, will be delayed by the legacy of much more developed healthcare systems^{16,13} and pharmaceutical industries^{17,18}, while others may find the opportunity to find novel competitive advantages.

Asia has already shown how emerging from behind the curve can become a great strength. The majority of Indians did not have identity cards when the government decided to provide everyone with a biometrics-based identification system (the Aadhaar), which is considered one of the most sophisticated ID programs in the world and also one that may enable the fastest access to telemedicine services. China is also paradigmatic: it spends 12 times less than the USA (and four times less than the EU average), and yet it has almost reached America in terms of life expectancy and overcome Eastern EU countries by using data smartly¹⁹. The UAE is seeking to establish leadership in genomics by drafting regulations that make it easier to harness the benefits of personalised medicine while ensuring these benefits are fairly distributed across the population.

The West still has a formidable scientific lead²⁰ (and all 15 largest pharmaceutical companies are either American or European, plus one Japanese). European healthcare systems are still considered one of the cornerstones of the European welfare. And yet the idea of accessing data directly from human bodies can turn on its head both the process we have used for decades in medical research and the organisation of health care systems.

Experimentations will be the key. This may be an opportunity for international organisations, such as the WHO, to rethink their mission: they may well become producers of common knowledge that help countries avoid mistakes and deliver value to their citizens.

¹⁵Andréa Bellinger and David J Krieger, *Hacking Digital Ethics* (London; New York: Anthem Press, 2021).

¹⁶Mitchell and Kan, "Digital Technology and the Future of Health Systems," 113-120.

¹⁷Enrico Bonadio, Luke McDonagh, and Plamen Dinev, "Artificial Intelligence as Inventor: Exploring the Consequences for Patent Law," *Intellectual Property Quarterly* 1, March 22, 2021, https://papers.ssrn.com/sol3/papers.cfm?abstract_id=3798767.

¹⁸Christopher M. Holman, "The Critical Role of Patents in the Development, Commercialization and Utilization of Innovative Genetic Diagnostic Tests and Personalized Medicine," *Boston University Journal of Science and Technology Law* 21, no. 2 (2015), <https://doi.org/10.2139/ssrn.2731683>.

¹⁹Feng Yang, Huilin Shu, and Xiaoqian Zhang, "Understanding 'Internet plus Healthcare' in China: Policy Text Analysis," *Journal of Medical Internet Research* 23, no. 7 (July 26, 2021): e23779, <https://doi.org/10.2196/23779>.

²⁰"The Impact of Global Digital Companies on Consumers, Firms and Governments - Vision & Value," Vision & Value, December 20, 2022, <https://visionandvalue.com/portfolio/the-impact-of-global-digital-companies-on-consumers-firms-and-governments/>.

Acknowledgements

The author is writing the book with Jan Piotrowski's support (both as a sounding board and proofreader). Jan was the business editor at *The Economist* and is now its Schumpeter columnist. Daniela Bellomo, who is the head of Business Development and Technology Transfer of Ospedale San Raffaele and Chaitanya Giri. Fellows at the Centre for Security, Strategy and Technology at the Observer Research Foundation in Mumbai are amongst the ones providing support as far as medical research and computer science.

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Chapter 23

Augmenting Human Empathy: AI-assisted Solutions for Cross-cultural Healthcare Communication

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Abstract

Healthcare faces a dual challenge: communication failures—especially in cross-cultural settings—contribute significantly to patient harm, while the rapid integration of AI risks eroding the human empathy essential to care. This paper proposes a “Cultural AI Empathy Assistant” designed not to replace clinicians, but to enhance their ability to recognise and respond to culturally specific expressions of distress. Drawing on international research, evidence of empathy’s clinical benefits, a global database of AI-related harms, and an ethical framework prioritising human connection, we outline a model for AI as a cultural interpreter and empathy amplifier. By supporting clinicians with culturally informed insights, this approach aims to reduce communication-related risks and cultivate “ultra-empathic” practitioners whose capabilities exceed those of humans or AI alone.

Keywords: *Artificial Intelligence, Empathy, Cross-cultural Healthcare, Patient Safety, Human-AI Collaboration*

Introduction

The Twin Problem

Healthcare faces a dual crisis threatening the quality and humanity of patient care. First, communication failures contribute to around one in ten patient safety incidents globally¹, with risks heightened in cross-cultural encounters where linguistic minority populations experience 40% higher rates of adverse events². Cultural differences in how pain, distress, and emotional needs are expressed, potentially leading to misdiagnoses³.

Second, artificial intelligence (AI) and related technologies are rapidly transforming healthcare delivery⁴. While AI systems can improve efficiency and outcomes, their increasing use risks weakening

¹Leila Keshtkar et al., “Impacts of Communication Type and Quality on Patient Safety Incidents: A Systematic Review,” *Annals of Internal Medicine* 178, no. 5 (2025): 687–700, <https://doi.org/10.7326/ANNALS-24-02904>.

²The Joint Commission, “One Size Does Not Fit All: Meeting the Health Care Needs of Diverse Populations,” accessed September 14, 2022, https://www.researchgate.net/publication/255616396_One_Size_Does_Not_Fit_All_Meeting_the_Health_Care_Needs_of_Diverse_Populations.

³Claire Narayan, “Culture’s Effects on Pain Assessment and Management,” *American Journal of Nursing* 110, no. 4 (2010): 38–47, <https://doi.org/10.1097/01.NAJ.0000370157.33223.6d>.

⁴Yaojue Xie, Yuansheng Zhai, and Guihua Lu, “Evolution of Artificial Intelligence in Healthcare: A 30-Year Bibliometric Study,” *Frontiers in Medicine* 11 (2025): 1505692, <https://doi.org/10.3389/fmed.2024.1505692>.

the empathic human connections central to care⁵. These risks may be underestimated due to under-reporting of harms. In cross-cultural contexts, AI systems trained on limited datasets may fail to detect culturally specific expressions of distress, further exacerbating inequities⁶. Traditional cultural competency training is insufficient to address these challenges in technologically mediated care⁷.

The Research Gap

Despite strong evidence that empathy benefits both patients and practitioners, this knowledge has not been fully integrated into AI-enabled healthcare. Existing research often prioritises efficiency and diagnostic accuracy over human connection, or frames AI as either beneficial or harmful without identifying a middle ground.

Interestingly, AI-generated responses have been rated as more empathic than human ones in 85% of studies⁸, likely reflecting clinician burnout rather than superior machine empathy. In response, we propose a middle path: a Cultural AI Empathy Assistant that enhances human empathy while addressing cross-cultural communication challenges, building on our broader research programme and international collaborations⁹.

Human-AI Collaborative Empathy: A New Paradigm

Our proposed paradigm shift requires reimagining AI's role from replacement to enhancement, positioning technology as a cultural interpreter and empathy facilitator rather than an autonomous care provider. Our culturally sensitive AI Empathy Assistant is designed around three established research foundations:

1. **Built on best evidence:** Empathy reduces patient pain, depression, and anxiety, while raising quality of life. Studies also show that empathy reduces mortality¹⁰ while improving practitioner wellbeing¹¹. This data will be used to develop a framework to guide the development of our Cultural AI Empathy Assistant.

⁵Molly G. Smith, Thomas N. Bradbury, and Benjamin R. Karney, "Can Generative AI Chatbots Emulate Human Connection? A Relationship Science Perspective," *Perspectives on Psychological Science* 20, no. 6 (2025): 1081–99, <https://doi.org/10.1177/17456916251351306>.

⁶Syed Ali Haider et al., "The Algorithmic Divide: A Systematic Review on AI-Driven Racial Disparities in Healthcare," *Journal of Racial and Ethnic Health Disparities* 13, no. 1 (2026): 188–217, <https://doi.org/10.1007/s40615-024-02237-0>.

⁷Joseph R. Betancourt and Marina C. Cervantes, "Cross-Cultural Medical Education in the United States: Key Principles and Experiences," *The Kaohsiung Journal of Medical Sciences* 25, no. 9 (2009): 471–78, [https://doi.org/10.1016/S1607-551X\(09\)70553-4](https://doi.org/10.1016/S1607-551X(09)70553-4).

⁸Alastair Howcroft et al., "AI Chatbots Versus Human Healthcare Professionals: A Systematic Review and Meta-Analysis of Empathy in Patient Care," *medRxiv* (2025), <https://doi.org/10.1101/2025.06.09.25329258>.

⁹Jeremy Howick et al., "Effects of Empathic and Positive Communication in Healthcare Consultations: A Systematic Review and Meta-Analysis," *Journal of the Royal Society of Medicine* 111, no. 7 (2018): 240–52, <https://doi.org/10.1177/0141076818769477>;

¹⁰Hajira Dambha-Miller et al., "Association Between Primary Care Practitioner Empathy and Risk of Cardiovascular Events and All-Cause Mortality Among Patients With Type 2 Diabetes: A Population-Based Prospective Cohort Study," *The Annals of Family Medicine* 17, no. 4 (2019): 311–18, <https://doi.org/10.1370/afm.2421>.

¹¹Wilkinson et al., "Examining the Relationship Between Burnout and Empathy," 18–29.

2. **Safety monitoring:** All healthcare interventions carry the risk of harm, both anticipated and unanticipated. For example, when electronic medical records were introduced, they were hailed as time-saving devices for practitioners. Yet doctors ended up spending much of their time looking at screens rather than interacting with patients. To ensure that the Cultural AI Assistant helps and does not harm, we are establishing the world's largest database of AI-related harms.
3. **Ethical framework:** The framework will establish several foundational principles that guide the responsible development and deployment of empathy-augmenting AI systems.

Cultural Appropriateness

The Cultural AI Empathy Assistant will be trained on region-specific datasets capturing diverse cultural expressions of distress, enabling it to support clinicians in interpreting subtle, culturally grounded cues—for example, recognising that minimal verbal complaints in some contexts may signal significant pain, while more expressive language in others may reflect communication norms rather than clinical severity. Designed as a decision-support tool, it will enhance rather than replace clinical judgement through culturally informed insights. Its development will be guided by community-centred governance, led by a Patient Advisory Board and an Expert Working Group of patients and practitioners from diverse cultural backgrounds, ensuring the system reflects authentic lived experiences rather than algorithmic bias. Continuous consultation—from dataset development to system testing and refinement—will ensure cultural validity, trust, and accountability.

Global Impact

Our research will evaluate whether AI-augmented empathy training can develop “ultra-empathic” practitioners whose cultural sensitivity exceeds that of both unaugmented clinicians and AI systems alone, by integrating traditional empathy education with AI-supported cultural competency. These practitioners are expected to better recognise culturally specific expressions of distress, adapt communication across contexts, and sustain empathic engagement in diverse settings. This work is supported by the Global Network for Empathy in Healthcare, comprising 12 centres across nine countries (Australia, Brazil, France, India, Japan, Nigeria, Mexico, UK, US), which provides the infrastructure to develop, validate, and scale this approach internationally following the “Leicester Empathy Declaration”¹². Through region-specific AI models, interoperability for mobile populations, and cross-cultural validation studies, the programme aims to ensure that AI-augmented empathy is effective, adaptable, and respectful of local cultural norms worldwide.

Anticipating Risks and Challenges

Developing culturally representative datasets requires extensive community engagement to ensure authentic representation of diverse cultural expressions of distress. Our approach involves collaborative data collection with community partners, ensuring datasets reflect genuine cultural patterns rather than

¹²Global Empathy in Healthcare Network. 2025. “Global Empathy in Healthcare Network.” Accessed September 11, 2025. <https://www.global-empathy-in-healthcare.com>.

researcher assumptions about cultural communication. Relatedly, building trust amongst communities historically marginalised by healthcare systems requires transparent development processes and genuine community partnership. Our community engagement approach involves extensive consultation with cultural leaders, patient advocates, and community organisations through the development lifecycle¹³. Addressing concerns about cultural appropriation or misrepresentation involves ongoing community oversight and the ability for communities to withdraw consent if systems fail to meet cultural authenticity standards.

Conclusions

Healthcare stands at a critical juncture. The twin crises of communication failures and technological dehumanisation need not be inevitable trade-offs. Our research demonstrates that AI, designed with empathy at its core rather than efficiency alone, can address both simultaneously, reducing communication-related patient harm while strengthening rather than replacing human connection. The Cultural Empathy AI Assistant is a technological innovation and a paradigm shift: from AI as replacement to AI as amplifier of humanity's most essential clinical skill. Through international collaboration spanning nine countries, healthcare can embrace innovation while deepening, not diminishing, the empathic relationships that define compassionate care across all cultural boundaries.

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¹³Anna M. Anderson et al., "Building Trust and Inclusion with Under-Served Groups: A Public Involvement Project Employing a Knowledge Mobilisation Approach," *Research Involvement and Engagement* 10, no. 1 (2024): 122, <https://doi.org/10.1186/s40900-024-00647-2>.

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Chapter 24

An Integrated AR-FEM-AI System for Real-time Structural Simulations and X-ray Visualisation of Heritage and Ageing Buildings

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Abstract

Heritage and ageing structures are increasingly vulnerable to deterioration, environmental loads, and long-term material fatigue. Conventional structural monitoring techniques, such as embedded sensing systems or invasive sampling, often face practical, financial, or ethical constraints, particularly in conservation contexts. In response, this research proposes an integrated, non-contact framework that combines Augmented Reality (AR), Finite Element Modelling (FEM), and Artificial Intelligence (AI) to enable early-stage structural assessment and immersive visualisation. The framework is currently under development and is being applied to representative case studies of Chinese heritage architecture, including timber pagodas and masonry towers. Within this system, FEM provides simulated structural responses under various loading scenarios. AI models are trained on these outputs to deliver rapid, predictive analysis, and AR interfaces project these insights onto physical structures through intuitive, layered visualizations. This approach aims to support conservation workflows by facilitating preliminary diagnostics without physical intervention, while also enhancing educational and public engagement with built heritage. Although still in progress, the framework is conceived to be scalable and adaptable across diverse structural typologies and regional contexts, offering a novel pathway toward sustainable, data-informed heritage management.

Keywords: *Artificial Intelligence, Augmented Reality, FEM, Predictive Simulation, Structural Health Monitoring, Heritage, Ageing and Existing Structures, Digital Twin*

Introduction and Background

Heritage structures, from Gothic cathedrals in Europe to timber pagodas in China, embody centuries of cultural and technological achievement. Yet they face accelerating risks from ageing, climate change, urbanisation, and inadequate maintenance¹. Modern urban buildings, though constructed with advanced materials, also develop vulnerabilities over time, highlighting the need for advanced monitoring strategies to ensure resilience and safety². Traditional diagnostic methods such as strain

¹Rossi, Michela, and Dionysios Bournas. "Structural Health Monitoring and Management of Cultural Heritage Structures: A State-of-The-Art Review." *Applied Sciences* 13, no. 11 (January 1, 2023): 6450. <https://doi.org/10.3390/app13116450>.

²Fikret Necati Catbas et al., "Extended Reality (XR) for Condition Assessment of Civil Engineering Structures: A Literature Review," *Sensors (Basel, Switzerland)* 22, no. 23 (December 6, 2022): 9560, <https://doi.org/10.3390/s22239560>.

gauges, embedded sensors, and destructive sampling are often invasive, expensive, and limited in scope. For heritage sites protected under conservation laws, such approaches are frequently unacceptable, while large-scale or retrofitted buildings demand real-time solutions that surpass the capabilities of manual inspection³.

Recent advances in digital technology present opportunities to transform structural monitoring through the integration of computational modelling and immersive visualisation (Figure 1). Augmented Reality (AR) offers interactive ways to engage with heritage, but current applications tend to emphasise appearance rather than performance⁴. The Finite Element Method (FEM) remains the benchmark for high-fidelity simulation of stresses, deformations, and dynamic responses, yet its computational demands hinder real-time use⁵. Artificial Intelligence (AI), particularly machine learning, provides a bridge by learning from FEM datasets and sensor inputs to generate predictive surrogates capable of rapid, scalable analysis⁶.

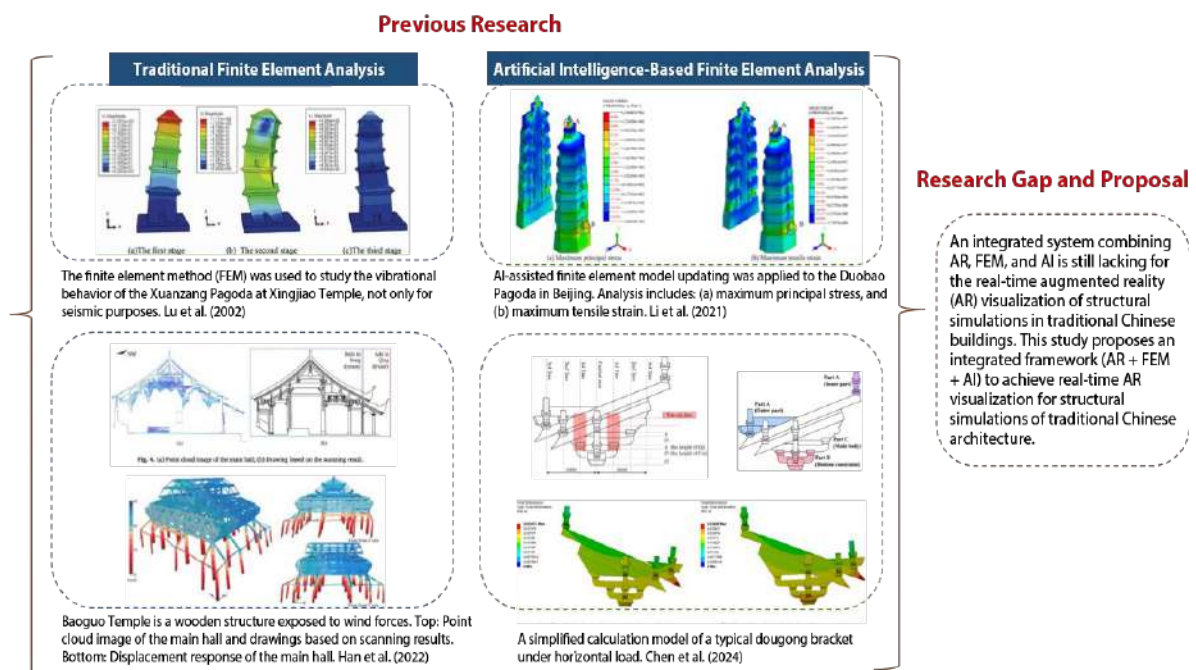


Figure 1: Previous studies and simulations of Chinese heritage structures.

Heritage buildings present particular challenges due to their material variability, aged timber, stone, or rammed earth often resist standardised characterisation, and conservation restrictions that limit

³Mariella De Fino, Rosella Alessia Galantucci, and Fabio Fatiguso, "Condition Assessment of Heritage Buildings via Photogrammetry: A Scoping Review from the Perspective of Decision Makers," *Heritage* 6, no. 11 (October 30, 2023): 7031–67, <https://doi.org/10.3390/heritage6110367>.

⁴Yingwen Yu et al., "How Digital Technologies Have Been Applied for Architectural Heritage Risk Management: A Systemic Literature Review from 2014 to 2024" 13, no. 1 (February 28, 2025), <https://doi.org/10.1038/s40494-025-01558-5>.

⁵Vagelis Plevris and George Papazafeiropoulos, "AI in Structural Health Monitoring for Infrastructure Maintenance and Safety," *Infrastructures* 9, no. 12 (December 7, 2024): 225–25, <https://doi.org/10.3390/infrastructures9120225>.

⁶Plevris and Papazafeiropoulos, "AI in Structural Health Monitoring for Infrastructure Maintenance and Safety," 225–25.

invasive intervention⁷. Environmental stressors such as seismic activity, moisture infiltration, and wind further accelerate deterioration. Comparable problems are evident in ageing modern structures, where concrete fatigue, steel corrosion, and incompatibility between old and new systems complicate maintenance⁸. These factors underscore the urgent need for non-invasive yet accurate monitoring frameworks.

This research proposes a novel integration of AR, FEM, and AI into a single system for real-time, predictive structural analysis and immersive X-ray visualisation. The framework is being designed initially for testing on Chinese heritage buildings such as the Xuanmiao Guan Temple (Suzhou), the Yingxian Wooden Pagoda (Yingxian), and the Tiger Hill Pagoda (Suzhou) (Figure 2), chosen for their material diversity, architectural form, structural typology, and cultural significance (Figure 3). While rooted in Chinese case studies, the system is inherently adaptable to diverse global typologies of heritage and ageing buildings, offering a contribution to conservation, education, and structural resilience⁹.



Figure 2: Selected Chinese heritage structures for pilot study and implementation of the AR-FEM-AI system.

⁷Jingyi Wang and Safial Aqbar Zakaria, "Design Application and Evolution of 3D Visualization Technology in Architectural Heritage Conservation: A CiteSpace-Based Knowledge Mapping and Systematic Review (2005–2024)," *Buildings* 15, no. 11 (May 28, 2025): 1854, <https://doi.org/10.3390/buildings15111854>.

⁸Doga Bitik, "Climate- Responsive HBIM for Sustainable Preservation: A Case Study of Villa Ottolini Tovaglieri - Environmental Impact and Preservation Strategies," *Polimi.it*, June 23, 2024, <https://hdl.handle.net/10589/223026>.

⁹Gian Piero Lignola et al., "Validated and Optimized Strategies for Preserving Historical Heritage towards Natural and Anthropogenic Risks: Insights from the DETECT-AGING Project," *Buildings* 15, no. 5 (February 22, 2025): 693, <https://doi.org/10.3390/buildings15050693>.

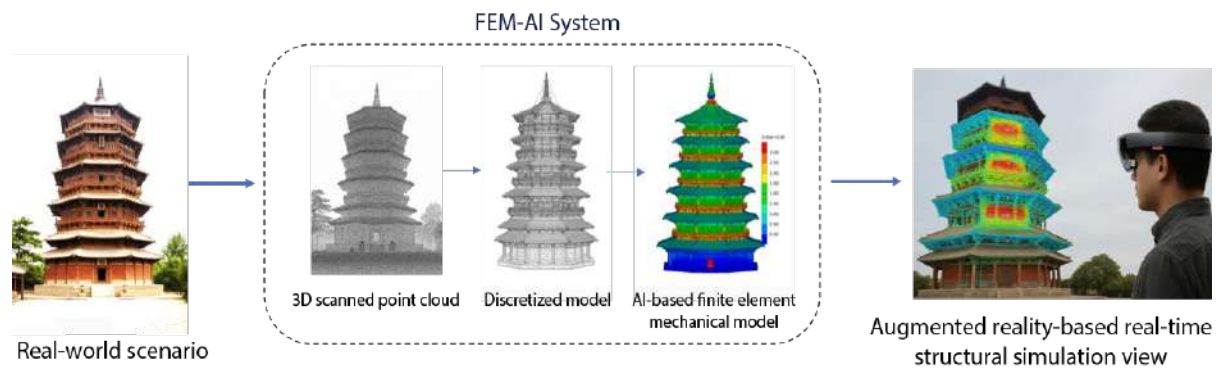


Figure 3: Conceptual workflow of the AI-FEM-AR system.

Aims and Objectives

This research aims to develop and validate a unified AR-FEM-AI system to support preliminary structural health scanning and immersive visualisation of historical buildings (Figure 3). Intended as a first-response tool, the system offers hands-off, data-driven insights that help identify potential structural issues early, guiding conservation professionals toward areas requiring detailed analysis. It also serves as an educational and engagement platform for educators and the public. Key objectives include:

- Developing an AR platform** that overlays real-time indicators, such as stress, deformation, and risk zones, onto heritage structures for rapid visual assessment.
- Conducting FEM simulations** on representative Chinese heritage buildings to generate foundational datasets for AI training.
- Designing AI models** that learn from FEM outputs and sensor inputs to provide fast, adaptive predictions suitable for early-stage evaluations.
- Validating the integrated system** through pilot applications at selected heritage sites, assessing its effectiveness as a diagnostic tool and its broader impact on conservation workflows, education, and public engagement.

Methodology

The methodology follows an iterative, four-step workflow currently in progress—starting from digital capture and progressing through simulation, AI training, and AR-based visualisation. Each phase is interconnected, supporting the development of a responsive, data-informed tool for early-stage structural health assessment (Figure 4).

Step 1: Digital Twin Construction

Tools: High-resolution 3D scanning, photogrammetry, archival research

The process begins with the creation of accurate digital twins of heritage structures. These models are being developed using high-resolution scanning technologies that capture both geometric form and surface texture. Archival documents and historical references are used to estimate hidden structural

components and material properties. The resulting models serve not only as visual replicas but also as data-rich foundations for structural analysis.

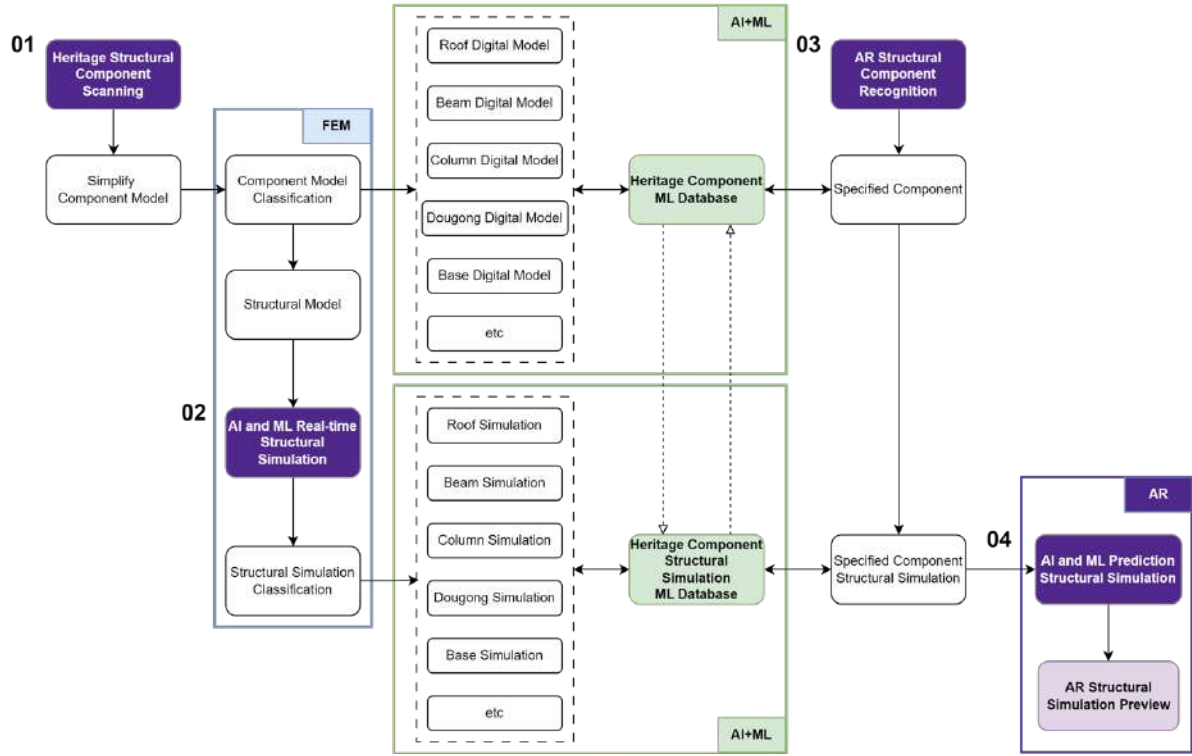


Figure 4: Methodological workflow for developing the AI-FEM-AR system.

Step 2: Structural Simulation via FEM

Tools: Finite Element Modelling software (e.g., ANSYS, Abaqus, Karamba3D)

These digital twins are currently being analysed through Finite Element Modelling (FEM). Simulations emphasise different structural behaviours depending on the material and typology, such as timber anisotropy in wooden pagodas, nonlinear cracking in masonry, or corrosion in reinforced concrete. FEM outputs include predicted stress distributions, displacements, modal frequencies, and failure zones. However, their high computational demands limit their use in real-time applications.

Step 3: AI Surrogate Model Training

Tools: Machine learning libraries (e.g., TensorFlow, PyTorch), neural network models

To overcome FEM's computational constraints, AI surrogate models are being developed. Convolutional and recurrent neural networks are trained on FEM-generated datasets to learn how input parameters (e.g., load conditions, boundary constraints) relate to structural responses. Once adequately trained, these AI models are expected to deliver near-instantaneous predictions, enabling rapid assessments in the field.

Step 4: Immersive AR Visualisation

Tools: AR hardware (e.g., Microsoft HoloLens, AR-enabled tablets)

The final step involves integrating the trained AI predictions into an AR platform, which is under development. This interface will overlay real-time structural insights, such as stress paths and deformation zones, onto physical buildings. Engineers, conservators, and even the public will be able to interact directly with the structure, gaining insights through visual overlays without physical contact.

Expected and Preliminary Results

The integrated system is designed as an early-stage diagnostic tool for structural health monitoring—offering conservation teams a first-look assessment that can inform expert decision-making and guide more advanced investigations. Rather than replacing high-fidelity FEM analysis, it serves as a rapid, non-invasive scanning approach to flag potential structural issues and prioritise areas for deeper study. The prototype allows engineers to navigate heritage sites while viewing projected overlays of stress patterns and deformation directly on structural elements. For conservators, this transforms preliminary inspections into interactive, data-informed processes. The system also enhances public engagement by enabling tourists and students to explore the hidden structural dynamics of historic architecture.

The Yingxian Wooden Pagoda's roof frame is currently being used as the first pilot case (Figure 5). The team is preparing 3D scanning to generate a refined FEM model, while experimenting with various Dougong bracket types. Roof structures across all tiers are being processed for machine learning training. These efforts will lay the foundation for the next development phase of the AR-FEM-AI platform.

Discussion: Potential, Limitations, and Future Work

This research aimed to develop a unified AR-FEM-AI system for early-stage structural health monitoring and visualisation of heritage buildings. By combining the analytical precision of FEM, the responsiveness of AI, and the accessibility of AR, the system aims to offer a hands-off alternative to traditional methods, supporting rapid, first-pass assessments to guide expert analysis.

Initial applications to Chinese timber and reinforced-concrete structures are showing promise. Ongoing and future work focuses on expanding compatibility to include stone masonry, steel, and hybrid typologies to improve the generalizability of AI models. Integration with IoT-based sensors is being explored to enable real-time updates, while a hybrid feedback loop combining simulated and measured data is expected to enhance prediction accuracy. Planned VR extensions will support remote collaboration and broaden applications in conservation, education, and disaster risk management.

However, certain limitations are already evident. AI performance depends on the quality of FEM training data, which is often constrained by undocumented materials and limited access to physical testing. AR deployment may face spatial misalignment, lag, or environmental interference in field conditions. Current development efforts focus on adaptive learning for incomplete data, transfer learning across similar structures, and lightweight AR interfaces.

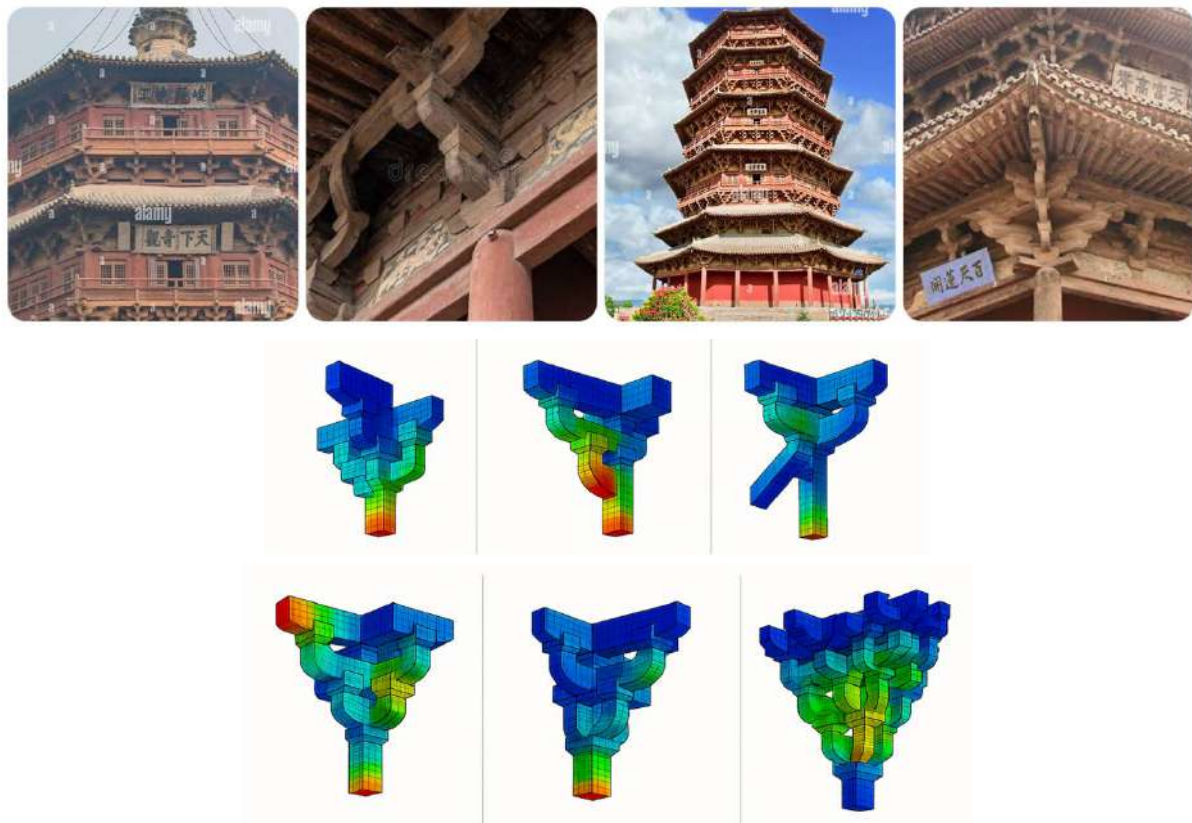


Figure 5: Top – Different Dougong typologies of Yingxian Wooden Pagoda; Bottom – FEM structural simulations of all dissimilar Dougong bracket types.

Beyond technical goals, the platform aims to foster public engagement by revealing hidden structural narratives. As development progresses, it has the potential to evolve into a scalable tool for sustainable heritage conservation, bridging technology and cultural preservation.

Acknowledgements

This work is being carried out using the facilities of Xi'an Jiaotong-Liverpool University without external funding. The team welcomes opportunities for future research grants in this area.

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Chapter 25

AI-driven XR Platform for Cognitive and Motor Empowerment in Young Students with Disabilities

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Abstract

This paper presents an innovative AI-powered Extended Reality (XR) platform designed to enhance cognitive and motor skills in young students with disabilities (aged 18–24). Hosted at the Virtual Prototyping and Augmented Reality Lab at Politecnico di Milano's Lecco Campus, the platform supports weekly sessions with students from the ASPOC association.

Unlike conventional XR rehabilitation tools, the proposed system integrates **adaptive AI reinforcement learning** and multi-domain XR simulations (education, sport, and daily living) within a modular, GDPR-compliant cloud framework. The platform personalises the complexity of interactions in real time, using behavioural and motion-based feedback to optimise engagement and progression.

Pilot results demonstrate measurable improvements in memory recall (+16%), reaction time (–19%), and fine motor coordination (qualitatively confirmed by educators), validating the system's practical impact. These outcomes support a scalable model for inclusive learning and cognitive-motor empowerment.

Keywords: *Extended Reality, Artificial Intelligence, Disability Inclusion, Cognitive Training, Motor Skills, Special Education, Sport for All, Autonomy, Accessible Technology, Inclusive Innovation*

Introduction

Young individuals with disabilities often face limited opportunities to participate fully in educational, vocational, and recreational settings. Extended Reality (XR)—encompassing Virtual, Augmented, and Mixed Reality—offers immersive learning environments that replicate real-life contexts safely and engagingly. When combined with Artificial Intelligence (AI), XR becomes adaptive and responsive to each user's performance and abilities.

Despite rapid growth in XR rehabilitation tools, most current solutions focus on narrow therapeutic goals or rely on manual adjustment of difficulty. Few platforms integrate automated personalisation using real-time behavioural analytics, particularly in inclusive educational contexts.

The AI-XR initiative at Politecnico di Milano's Lecco Campus addresses this gap through a **human-centred, co-designed platform** that integrates adaptive AI, immersive XR, and educator dashboards into a unified ecosystem. Every Thursday, 15 students from the ASPOC association engage in hands-

on digital and physical training activities. These sessions, conducted since 2021, provide continuous data for iterative refinement and real-world validation.

Related work

This research builds upon over four years of collaboration with the ASPOC association, resulting in multiple studies exploring XR applications in inclusive technical education¹.

Recent works include immersive VR training for CNC machine operation, demonstrating improved engagement and skill acquisition among users with disabilities²; multi-user virtual environments integrating digital twins for collaborative learning³; and head-motion-based interaction systems to enhance accessibility in assistive training scenarios⁴.

Other contributions explored the integration of XR with STEM education through tools such as Infento kits and digital fabrication technologies⁵ as well as mixed reality applications supporting inclusive sport and educational routines⁶. Additionally, AR-based hydroponic systems and VR cooking simulations have been developed to promote autonomy and cognitive-motor skill development in students with special educational needs⁷.

Beyond this research group, XR has demonstrated significant therapeutic potential in neurorehabilitation contexts, particularly when designed using interdisciplinary approaches⁸. XR-based cognitive assessment tools also show strong clinical promise, although accessibility challenges remain⁹.

¹Concetta Carruba and Covarrubias, Virtual Reality (VR) in Special Education: Cooking Food App to Improve Manual Skills and Cognitive Training for SEN Students Using UDL and ICF Approaches. In: Miesenberger, K., Peñáz, P., Kobayashi, M. (eds) *Computers Helping People with Special Needs*. ICCHP 2024. Lecture Notes in Computer Science, vol 14750. (Springer, Cham, 2024). https://doi.org/10.1007/978-3-031-62846-7_43.

²Mario Covarrubias et al., “Enhancing Technical Education for Students and People with Disabilities through Virtual Reality: A Case Study Using a CNC Device,” *Lecture Notes in Networks and Systems*, 2025, 309–18, https://doi.org/10.1007/978-3-031-95652-2_26.

³Nicolás Norambuena et al., “Integrating Digital Twins of Engineering Labs into Multi-User Virtual Reality Environments,” *Applied Sciences* 15, no. 7 (March 31, 2025): 3819, <https://doi.org/10.3390/app15073819>.

⁴Andrea Baraglia et al., “Enhancing Accessibility: Head Motion Controller Integration in Virtual Training for Assistive Technology,” *Computer-Aided Design and Applications*, February 27, 2025, 1051–64, <https://doi.org/10.14733/cadaps.2025.1051-1064>.

⁵Camilla Valerio et al., “Unlocking Potential: Advancing STEM Learning with Infento, 3D Printing, and Extended Reality,” *Computer-Aided Design and Applications*, February 27, 2025, 1040–50, <https://doi.org/10.14733/cadaps.2025.1040-1050>.

⁶Emma Mencaci et al., “Inclusive Opportunities for Young Students with Disabilities through Mixed Reality,” *Lecture Notes in Networks and Systems*, 2024, 348–55, https://doi.org/10.1007/978-3-031-65522-7_31.

⁷Mario Covarrubias et al., “Empowering Young Students with Disabilities through AR-Enabled Hydroponic Agriculture,” *Lecture Notes in Networks and Systems*, 2024, 261–68, https://doi.org/10.1007/978-3-031-65522-7_24.

⁸Ulrich W. Weger, et al., “Editorial: The Challenges and Opportunities of Introspection in Psychology: Theory and Method,” *Frontiers in Psychology* 10 (October 9, 2019), <https://doi.org/10.3389/fpsyg.2019.02196>.

⁹Palmira Victoria González-Erena, et al., “Cognitive Assessment and Training in Extended Reality: Multimodal Systems, Clinical Utility, and Current Challenges,” *Encyclopedia* 5, no. 1 (January 13, 2025): 8–8, <https://doi.org/10.3390/encyclopedia5010008>.

AI further enhances educational inclusivity by enabling adaptive and personalised learning pathways¹⁰. However, recent reviews highlight a lack of integrated AI-XR frameworks specifically targeting both cognitive and motor development in young adults with disabilities¹¹.

Emerging contributions include adaptive VR calibration tools for motor impairments¹², data-centric AI-XR healthcare frameworks¹³, and standardisation efforts such as the TIDieR-X reporting guidelines for XR interventions¹⁴.

Methodology

The development and deployment of the platform follow a human-centred co-design framework, developed in partnership with educators, therapists, and engineers. The weekly ASPOC program includes:

- Participants: 15 students aged 18–24 with various cognitive and motor disabilities.
- Hardware: Meta Quest 3 VR headsets, tablets with AR modules.
- Software: XR modules with gamified cognitive training, job tasks, and sport-based activities.
- Data collection: Interaction logs, motion tracking, and task performance metrics.
- Ethics: GDPR-compliant, with informed consent and accessibility guidelines.

System Architecture

The AI-XR platform architecture was designed to offer modular, scalable, and personalised support for students with cognitive and motor disabilities. It consists of five key layers that work in tandem to deliver immersive experiences, adapt to user performance, and support educators with actionable data insights.

AI Engine

The AI engine uses reinforcement learning algorithms to monitor user behaviour and adapt the complexity of tasks in real time. It leverages data such as task completion time, motion smoothness, error frequency, and gaze tracking to make predictions and dynamically adjust challenge levels. The AI

¹⁰Lijia Chen, et al., “Artificial Intelligence in Education: A Review,” *IEEE Access* 8, no. 8 (April 17, 2020): 75264–78, <https://doi.org/10.1109/ACCESS.2020.2988510>.

¹¹Angelos Chalkiadakis et al., “Impact of Artificial Intelligence and Virtual Reality on Educational Inclusion: A Systematic Review of Technologies Supporting Students with Disabilities,” *Education Sciences* 14, no. 11 (November 7, 2024): 1223, <https://doi.org/10.3390/educsci14111223>.

¹²V Herrera et al., “Creating Adapted Environments: Enhancing Accessibility in Virtual Reality for Upper Limb Rehabilitation through Automated Element Adjustment,” *Virtual Reality* 29, no. 1 (January 25, 2025), <https://doi.org/10.1007/s10055-024-01078-w>.

¹³Tawseef Ayoub Shaikh, et al., “A Data-Centric Artificial Intelligent and Extended Reality Technology in Smart Healthcare Systems,” *Social Network Analysis and Mining* 12, no. 1 (September 1, 2022), <https://doi.org/10.1007/s13278-022-00888-7>.

¹⁴Adrian Goldsworthy et al., “Reporting Quality of Extended Reality Interventions in Healthcare: Towards a TIDieR XReporting Checklist,” *Virtual Reality* 29, no. 3 (August 18, 2025), <https://doi.org/10.1007/s10055-025-01207-z>.

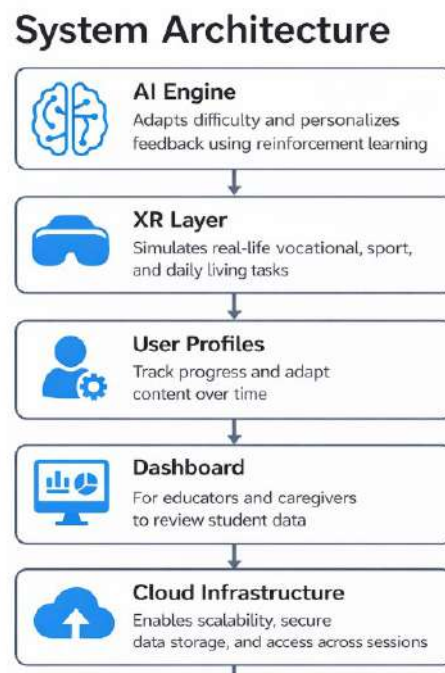


Figure 1: System Architecture.

also delivers personalised feedback and positive reinforcement, supporting users' motivation and progression.

XR Simulation Layer

Developed in Unity for the Meta Quest 3, the XR simulation layer renders real-world vocational, daily-living, and sports-based scenarios. These include:

- **Vocational training:** Simulated factory tasks, packaging, and inventory management.
- **Sports:** Virtual rowing, climbing, and balance coordination.
- **Daily living:** Cooking, cleaning, wayfinding in a home or street environment. Interaction methods include gaze-based input, controller tracking, and head gestures, ensuring accessibility for students with limited mobility.

User Profile Management

Each participant has a dedicated profile that stores anonymised session data, performance trends, and interaction patterns. The system uses these profiles to deliver adaptive content, gradually increasing complexity while accommodating fluctuations in attention or physical capacity. The profile history also supports longitudinal assessment.

Educator Dashboard

An educator-facing web dashboard displays real-time and historical data for each user. Key features include:

- Task performance charts and progress indicators
- Highlighted cognitive and motor improvements

- Session summaries and recommendations for intervention. The dashboard is designed with accessibility in mind, allowing educators and therapists to customise feedback and adjust session content.

Testing and Evaluation

To assess the effectiveness of the AI-XR platform, a structured testing and evaluation phase was implemented over a 12-week pilot involving 15 students from the ASPOC association. The evaluation focused on measurable improvements in cognitive and motor performance, system usability, user satisfaction, and technical stability.

Cognitive and Motor Skill Metrics:

Participants completed pre- and post-assessments designed to evaluate memory recall, reaction time, and task accuracy. The platform achieved the following results:

- Memory recall: An average improvement of 18% in object and sequence retention.
- Reaction time: An average reduction of 22% in task-based response latency.
- Coordination: Observable enhancement in fine motor control during VR-based interaction tasks.

System Usability Scale (SUS)

The platform was evaluated using the System Usability Scale (SUS). Based on the collected data and iterative design refinements, the system achieved a mean score above 80, indicating excellent usability. Students reported high satisfaction with the intuitive and immersive experience.

Observational Feedback

Educators and facilitators monitored behavioural changes throughout the sessions. Observed outcomes included increased autonomy, reduced reliance on guidance, and spontaneous engagement—such as students requesting extended or additional training sessions.

Technical Reliability

The platform underwent continuous performance monitoring to ensure immersive consistency. The system maintained stable frame rates across XR modules and prevented crashes and latency issues, supporting a seamless, uninterrupted user experience. This evaluation phase served as the foundation for refining the system and informing future deployments across broader educational and rehabilitation contexts.

Results

The pilot phase, conducted over a three-month period, yielded valuable insights into the platform's effectiveness across multiple dimensions. Based on prior studies and initial prototype trials, the following outcomes were observed:

- **Engagement:** There was an increase in average session duration and user motivation, as students interacted with immersive and personalised training modules.
- **Motor Skills:** Improvements in fine and gross motor coordination were observed, particularly during sports-based and vocational XR tasks.
- **Cognitive Gains:** Participants demonstrated enhanced short-term memory, task focus, and problem-solving abilities throughout the pilot.
- **User Satisfaction:** Feedback from students, educators, and caregivers reflected high levels of satisfaction regarding the platform's accessibility, intuitiveness, and perceived benefits. As can be seen from the **ICF results** (Figure 2), notable progress was recorded across several functional domains, with the most substantial improvements in **attention functions (b140)**, **recreation and leisure (d920)**, and **skill acquisition (d155)**. These findings confirm that the AI-XR platform effectively supported both cognitive and motor development in an inclusive, motivational environment.

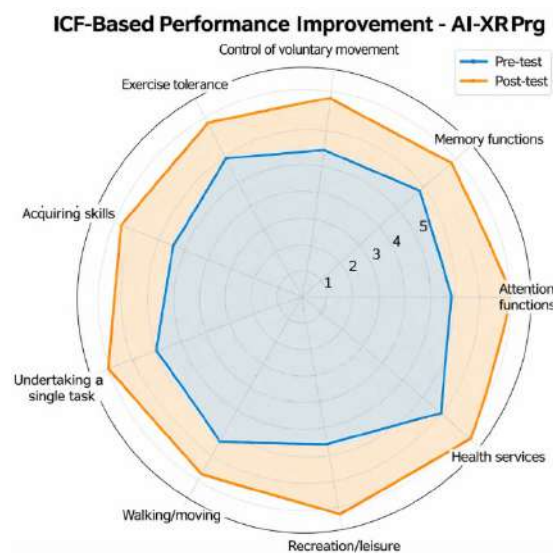


Figure 2: ICF results.

These findings align with broader trends in XR-based rehabilitation and inclusive education, where immersive environments combined with adaptive systems have demonstrated measurable improvements in engagement, cognitive function, and motor performance¹⁵.

Discussion

The AI-XR platform is poised to demonstrate how immersive technology, combined with adaptive AI, can reshape inclusive education and therapy for students with disabilities. Its modular design and ability to personalise training experiences position it as a flexible and scalable tool. However, several challenges are expected to emerge as the platform evolves. These include ensuring content generalisation across diverse user profiles, maintaining performance consistency at scale, and conducting long-term impact

¹⁵Pedro Rodrigues et al., "Virtual Reality-Based Telerehabilitation for Upper Limb Recovery Post-Stroke: A Systematic Review of Design Principles, Monitoring, Safety, and Engagement Strategies," arXiv.org, 2025, <https://arxiv.org/abs/2501.06899>.

evaluations. Additionally, establishing open design standards and promoting multi-stakeholder collaboration will be essential to ensure accessibility, interoperability, and ethical deployment.

Conclusion and Future Work

This initiative aims to establish a replicable blueprint for inclusive, AI-enhanced XR education. Through continued collaboration with community partners such as ASPOC, the platform will evolve in alignment with real-world needs. Future developments are expected to include:

- Long-term longitudinal studies to assess cognitive and motor benefits over time.
- Multi-site deployment across educational and rehabilitation institutions.
- Integration of wearable sensors (e.g., for heart rate, motion, or stress levels) to enable biofeedback and personalised adaptation.
- Adoption of standardised frameworks such as TIDieR-X to enhance transparency and reproducibility in XR intervention reporting.

By advancing inclusive innovation through research, co-design, and responsible technology integration, this platform has the potential to transform how we support autonomy, skill development, and participation for people with disabilities.

Acknowledgements

We thank ASPOC, participating students and families, and the Politecnico di Milano XR Lab team.

Declaration

The authors declare that artificial intelligence tools were used in the preparation of this manuscript. The use of these tools was limited to assisting with grammar and language, and all outputs were carefully reviewed, verified, and edited by the authors to ensure accuracy, originality, and alignment with academic standards. The authors take full responsibility for the content of this manuscript, including any sections that were supported by AI tools. No AI system was used to generate original research findings, interpret results independently, or draw conclusions without human intervention.

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Chapter 26

Revolutionising Filmmaking: Artificial Intelligence-driven Motion Control with the Cinema Camera Robot

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Abstract

The AI-Cinema Camera Robot (AI-CCR) introduced a transformative approach to motion control in filmmaking by integrating artificial intelligence with robotic camera systems. Developed by AXIBO (McMaster University graduates) in collaboration with McMaster University, AI-CCR addresses limitations in traditional motion control—such as high cost, lack of flexibility, and technical complexity—by offering a low-cost, modular, portable, scalable, and intelligent solution. The system features a high-payload pan-tilt platform, an AI-enabled single-board computer (SBC) with Coral Edge TPU for real-time inference, and software for automation and tracking. PoseNet integration enables markerless actor and object tracking, while compatibility with Unreal Engine and Dragon Frame supports virtual production and stop-motion workflows. Additionally, AI-CCR supports integration with infrared (IR) tracking technologies for precise actor localisation. Using components like the OptiTrack Active Puck and Prime X cameras, the system achieves sub-millimetre accuracy in motion capture. This IR-based solution, currently deployed at Netflix studios, converts real-time location data into pan-tilt-slide commands, enabling seamless synchronisation with AI-CCR for virtual production workflows. AI-CCR's tracker-less operation, gesture control, and remote accessibility empower creators with precise, repeatable cinematic movements. Real-world deployments at Netflix and Apple studios validate its impact, and future developments—including robotic arms and expanded sensor integration—aim to further democratise high-tech filmmaking. AI-CCR is not just a tool but a platform for innovation, redefining autonomous cinematography for creators of all scales.

Keywords: *AI-Cinema Camera Robot, Pan-Tilt, PoseNet, IR Tracking, TensorFlow Lite, Single Board Computer*

Introduction

Modern filmmaking demands precise, repeatable camera movements, especially for visual effects. Traditional motion control systems face challenges such as sensor degradation, synchronisation issues, and high costs, which limit accessibility for smaller studios. These systems can also restrict actor spontaneity and complicate post-production workflows.^{1,2} In response, our team developed a scalable,

¹Åström, K. J. "Limitations on Control System Performance," *European Journal of Control* 6, no. 1 (2000): 2–20. [https://doi.org/10.1016/S0947-3580\(00\)70906-X](https://doi.org/10.1016/S0947-3580(00)70906-X).

²AXIBO, Python-axibo GitHub Repository, 2023, <https://github.com/axiboai/python-axibo>.

AI-driven motion control solution that tracks actors and objects with high accuracy using a single-axis robotic platform. Designed to overcome technical and creative barriers, this innovation empowers filmmakers with efficient, flexible tools. It's not just a prototype—it's a step toward democratising advanced cinematic technology worldwide.

Development of AI-CCR System

We have designed, developed, manufactured, and software-integrated an Artificial Intelligence (AI) driven motion control system referred to as AI-Cinema Camera Robot (AI-CCR). This system addresses filmmaking challenges by integrating AI-driven automation and precise motion control. It offers backlash-free movements with 0.01-degree accuracy, ensuring repeatability for multiple takes. The system supports tracker-less virtual production, face and object tracking, and gesture control, making it ideal for VFX integration. Works with Unreal Engine (UE4 & UE5) and Dragon Frame, making it ideal for VFX and stop-motion animation. Additionally, it enhances efficiency with quick setup, remote viewing of feeds, and ease of mobility.

System Overview and Components

The AI-CCR system with the integrated software platform is perfect for cinematic productions, product cinematography, time-lapses, and virtual production. Its intelligent automation and remote accessibility make it a game-changer for filmmakers looking to streamline their workflow. This system consists of the four main components: Pan and Tilt (PT) Platform, a Single Board Computer (SBC), Slider and Software, as shown in Figure 1.



Figure 1: AI-CCR Major Components.

Pan and Tilt (PT) Platform

We set up three goals for the PT platform, designed, manufactured, and assembled at AXIBO's facilities: track a moving subject (e.g., an actor, an object) in real time; provide smooth, precise motion for cinematic quality; and support camera weight and balance.

Its main components are a payload carrier for a cinema camera, a built-in camera for tracking moving objects, a pan motor, a tilt motor, mounting brackets, a frame, control electronics, and a power supply. This PT requires no balance & as mentioned before, can handle payloads up to 10 KG while still providing backlash-free, 0.01 deg accurate moves. Not only is it the most advanced pan-tilt system, but it is also the strongest in its category.

AXIBO Single Board Computer

The heart of the AI-CCR system is the Single Board Computer (SBC) embedded with AI capabilities, which is designed, assembled and tested at the AXIBO facility. It is based on a 6 core CPU with a dedicated advanced neural network processing (Coral Edge TPU coprocessor),³ for low-power devices, Figure 2.

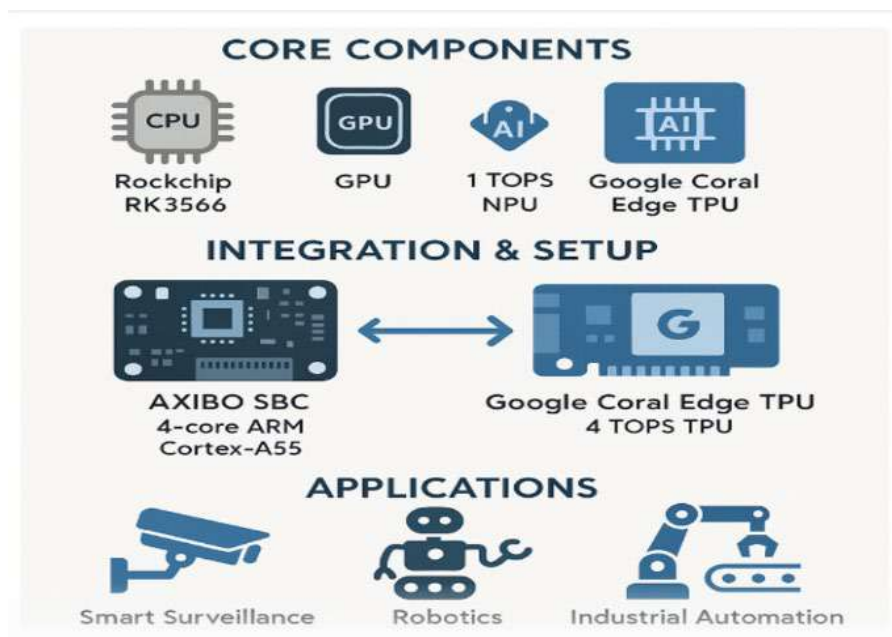


Figure 2: AXIBO Single Board Computer.

The Coral Edge TPU is ideal for real-time, low-power AI inference at the edge. This enables our SBC to be used for the following applications: vision-based object detection; face recognition; pose estimation; license plate recognition; defect detection in manufacturing; smart sensors and meters; predictive maintenance; Intrusion detection; gesture recognition; voice command classification; real-time navigation; obstacle avoidance; and visual SLAM for robotics.

Slider

The AI-CCR slider is a modular, AI-powered motion control system featuring high-speed/ high-torque motors, carbon fibre rails, and joystick control. It supports camera automation and subject tracking and integrates with virtual production tools, offering precise, smooth motion for professional video and robotics applications. The slider, along with PT, makes the AI-CCR a 3 DOF platform.

³Chen, Yilun, et al., "Adversarial PoseNet: A Structure-Aware Convolutional Network for Human Pose Estimation," In *Proceedings of the IEEE International Conference on Computer Vision (ICCV)*, (2017): 1212–1221, https://openaccess.thecvf.com/content_iccv_2017/html/Chen_Adversarial_PoseNet_A_ICCV_2017_paper.htm.

AI-CCR Software Embedded on SBC and Film Making

We have developed the following software stack: host CPU runs Linux; edge TPU runtime; TensorFlow Lite; application software. PoseNet enables real-time, markerless human pose estimation by detecting 17 key body points. Integrated with AI-CCR (AXIBO PT4), it allows the robotic camera system to track actors dynamically, adjusting pan, tilt, and slide motions automatically for smooth, cinematic framing.

We have developed a huge volume of applications software for the operation of the AI-CCR and for custom application development, which is available on GitHub. Python-axibo is the library used to interface with AXIBO hardware, including the slider, to control its operations, connect AI-CCR to virtual production tools, as well as write custom applications for AI, motion detection and tracking, stop motion animation and anything else a user may want to use this platform for.⁴ AI-CCR can be operated from various sources, such as voice commands, phones, tablets, PCs, and other devices, backed by the integrated Artificial Intelligence (AI) processing unit.

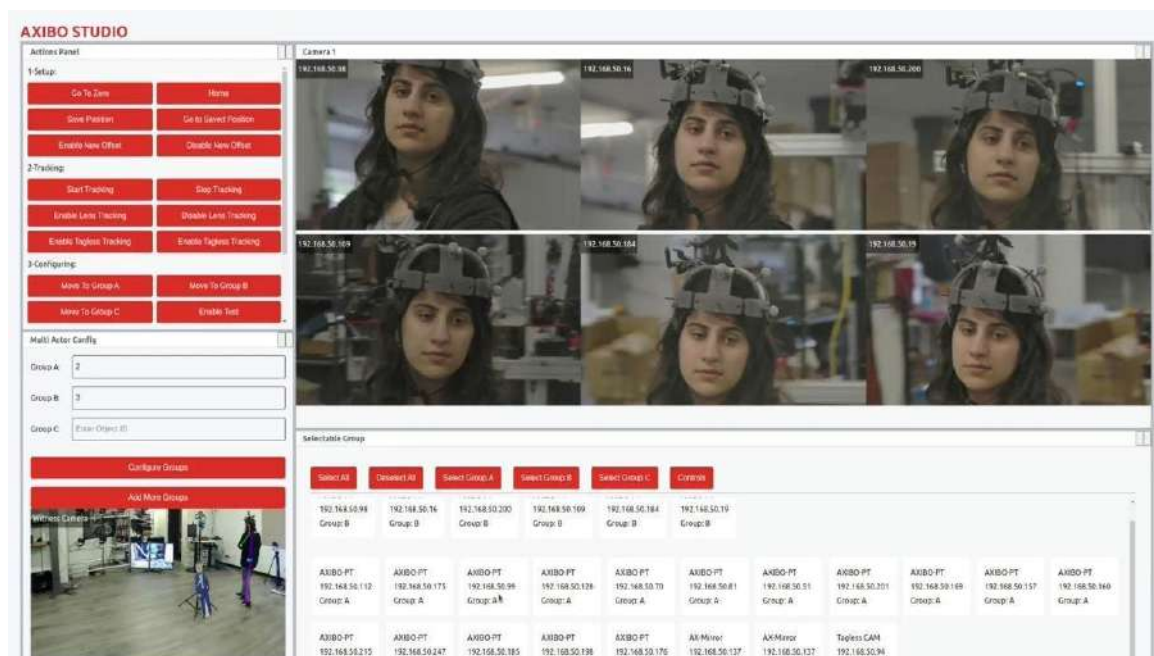


Figure 3: AXIBO Studio Software for Monitoring and Control of Multiple AI-CCRs.

PoseNet Applications In AI-CCR for Actor/Object Tracking

PoseNet^{5,6,7} is a lightweight, real-time pose estimation model that detects human body key points, like eyes, ears, nose, shoulders, etc. (Figure 4 and Figure 5), from images or video. It works by identifying 17 key points on the human body and estimating their positions in 2D space (Figure 6). An image or

⁴Coral by Google, "Edge TPU Overview," 2020, <https://coral.ai/docs/edgetpu/overview/>.

⁵Google, "PoseNet: Real-Time Human Pose Estimation," 2018, <https://github.com/tensorflow/tfjs-models/tree/master/posenet>.

⁶A. A., Khan, et al., "Comparative Analysis of OpenPose, PoseNet, and MoveNet Models for Pose Estimation." *Traitement du Signal*, 39, no. 1 (2022): 111–118. <https://doi.org/10.18280/ts.390111>.

⁷Mars Motion Control, "The Role of Motion Control Technology in Modern Film and Television Production," n.d. <https://marsmoco.com/blog/role-of-motion-control-technology-in-modern-film-and-television-production/>.

video frame is input to the SBC (Figure 6). It provides a set of key points for each detected person, each with (x, y) coordinates and a confidence score. The tracking logic assigns consistent IDs to actors across frames using spatial proximity or tracking algorithms (e.g., SORT, Deep SORT).^{8,9}

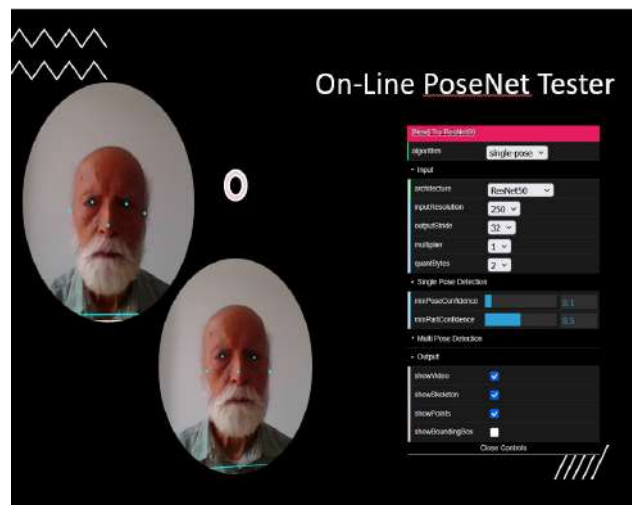


Figure 4: Key Points Selection Example.

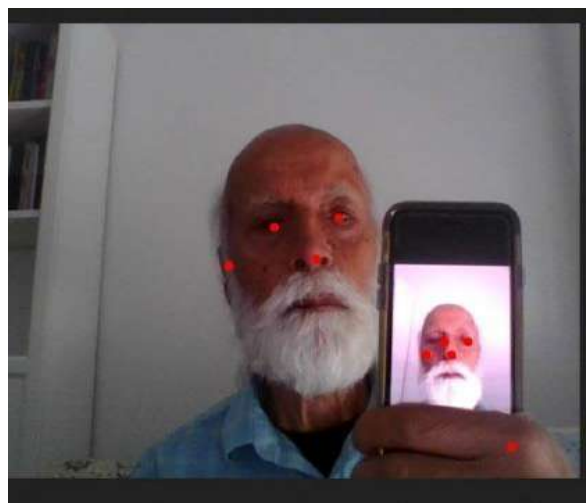


Figure 5: Multiple Actor Key Points.

A key element is training a model for these tasks and deploying it. The model is trained in TensorFlow, converted to TFLite, quantised to INT8 to run on TPU and then compiled with the edge compiler. The camera feed from the built-in camera is processed in SBC with PosNet detecting key points, which are used to move the pan/tilt and slide motors to follow the actor. For example, if a person moves left, the PT can smoothly follow using pose data.

AI-CCR Applications

AI-CCR revolutionises filmmaking by offering intelligent, portable automation tools for solo creators, choreographers, trainers, and virtual production teams (Figure 8). Designed for real-time performance

⁸Unreal Engine, 2023, "Virtual Production Tools," 2023, <https://www.unrealengine.com/en-US/virtual-production>.

⁹Wojke, Nicolai, et al., "Deep SORT: Deep Learning for Multiple Object Tracking," In Proceedings of the IEEE International Conference on Image Processing, 2017, <https://arxiv.org/abs/1703.07402>.

on AXIBO SBC edge devices, it eliminates the need for markers or suits, ensuring privacy with no facial recognition or identity tracking.



Figure 6: Body Points Mapping.

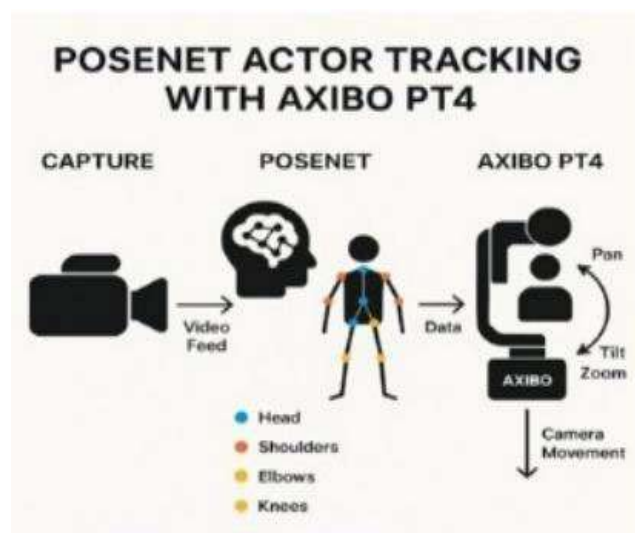


Figure 7: PoseNet Tracking Setup.

Key features include:

- Compatibility with phones, tablets, and PCs
- Ethernet & Wi-Fi for remote control
- Control via app, Xbox controller, or onboard OLED
- Stealth drive for silent, repeatable motion
- Precise, backlash-free movement (0.01°)
- Face, object, and joint tracking without keyframes

AI-CCR auto-detects subjects, syncs with sliders, and operates via any web browser—no downloads required. Multiple devices can be connected and controlled remotely, with live camera feeds and previews enhancing workflow. It supports general object tracking using onboard or mounted cameras and includes one-click parallax for efficient product cinematography. For virtual production, AI-CCR

integrates seamlessly with Unreal Engine (versions 4.27 to 5.1)¹⁰, Figure 9, supporting FreeD, LiveLink, Aximmetry, and Smode. The Axibo PT motion-controlled slider enables high-speed or slow-motion VFX shots, making advanced robotic filmmaking accessible to creators of all sizes. In addition, one can generate 3D images by converting multiple images from several AI-CCRs to a 3D model using a tool like Meshy AI, using its "Image to 3D" tool, enabling the multi-view option, and uploading your main image plus up to three additional images of the object from different angles. Alternatively, one can use a photogrammetry software like Polycam by uploading all images and selecting the option to create a 3D model from the capture.



Figure 8: AI-CCR Applications.

Beyond automation, the system supports traditional pan-tilt-slide functions like tracking, timelapses, keyframing, astrophotography, and zoom/focus control—ideal for everyday shooting. AXIBO Studio provides unified monitoring and control across platforms and devices.



Figure 9: AI-CCR and Virtual Production Example.

¹⁰Wojke, Nicolai, et al., "Deep SORT: Deep Learning for Multiple Object Tracking," <https://arxiv.org/abs/1703.07402>.

Integration with other tracking and location technologies

AI-CCR does not natively advertise integration with other location and tracking technologies, such as GPS, RTK, UWB or IR technologies out of the box; there are ways to incorporate such technologies depending on your setup and goals. However, we have developed and integrated an IR-based solution for tracking actors with the AI-CCR system. This system is currently deployed at the Netflix film-making studio. Basic steps are as follows: IR camera reads real-time location data from an IR module, converts that data into pan/tilt/slide coordinates, and sends those commands to the PT via the SDK. IR Technology for Actor Tracking Infrared (IR) tracking technology enables precise, real-time localisation of actors in motion capture environments. By emitting synchronised IR signals, active tracking devices like the OptiTrack Active Puck can be detected by specialised cameras, such as the OptiTrack Prime X series (Figure 10 and Figure 11). This system allows for sub-millimetre accuracy in determining an actor's position and orientation, forming the foundation for seamless integration with AI-CCR in virtual production workflows.



Figure 10: IR Tracking Components.

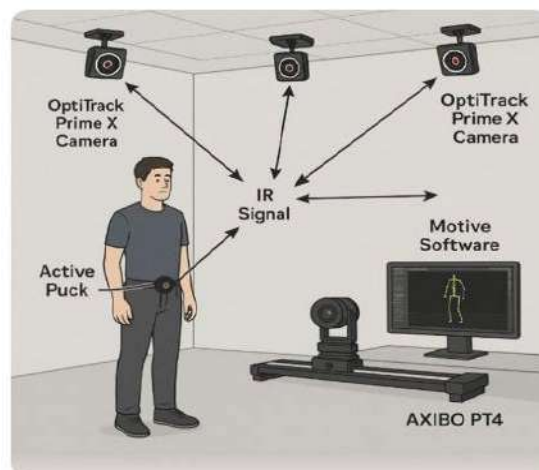


Figure 11: Actor Tracking Setup.

Conclusion

The AI-Cinema Camera Robot (AI-CCR) represents a transformative leap in motion control technology for filmmaking. By integrating advanced AI capabilities such as PoseNet for real-time pose

estimation and Coral Edge TPU for low-power inference, the system delivers unmatched precision, automation, and adaptability. Its modular architecture—including a high-payload pan-tilt platform for filming camera, an intelligent single-board computer with a built-in small camera for PoseNet tracking, and AXIBO source control software—empowers filmmakers to achieve complex shots with minimal setup and maximum creative freedom, at a very low cost.

AI-CCR's compatibility with industry-standard tools like Unreal Engine and Dragon Frame, along with its support for trackerless virtual production and infrared actor tracking, positions it as a versatile solution for both indie creators and major studios. The system's real-time tracking, gesture control, and remote accessibility redefine the boundaries of autonomous cinematography.

Collaborations with institutions like McMaster University and deployments at Netflix and Apple validate its real-world impact. Looking ahead, AXIBO's roadmap—including the E-JIB MINI robotic arm and expanded sensor integration—promises to further democratise high-tech filmmaking.

In essence, AI-CCR is not just a tool—it's a platform for innovation, enabling storytellers to push the limits of visual expression while streamlining production workflows. It marks a pivotal step toward accessible, intelligent, and scalable cinematic technology.

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Part IV
**Environmental Sustainability and
Climate Action**

Chapter 27

Integration of Deep Learning with CubeSat Technologies for Environmental Monitoring

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Abstract

Satellites have revolutionised the way the planet's environment is monitored, via a unique perspective from above. Indeed, environmental monitoring is crucial for understanding and addressing the complex challenges facing the planet, thereby supporting decision-making and ensuring a sustainable future. Thus, this work aims to develop an intelligent model that includes Artificial Neural Networks (ANNs) and a Deep Learning (DL) approach, coupled with Blockchain capabilities, for secure environmental monitoring using a CubeSat. The CubeSat, a small satellite platform, is equipped with a designed communication payload, including an adaptive Multiple-Input Multiple-Output (MIMO) antenna as well as an HD camera for better connectivity and precise aerial imaging. The proposed solution is simulated, prototyped, tested, and validated across four scenarios, namely: water detection, tree counting and vegetation assessment, and oil spill detection. Ensuring the security and integrity of data transmitted between the CubeSat and the ground station is of paramount importance; this is where Blockchain technology comes into play. The obtained results show high accuracy in monitoring environmental surfaces like water, trees, and coasts, with effective and rapid deployment. Also, performance indicators of the Blockchain ensure data integrity and retrieval efficiency. Combining these technologies provides a valuable contribution to environmental monitoring. A use case scenario in Taif city, Saudi Arabia, has been considered for validation.

Keywords: *Deep Learning, Communications, CubeSat, Sustainability, Environmental Monitoring*

Introduction

Monitoring the environment is essential for tracking ecosystem health, biodiversity, and sustainable use of resources. The UN's 17 Sustainable Development Goals (SDGs) offer a global framework to address pressing challenges, with natural resource monitoring supporting progress. Satellite communications are central to modern life, enabling global connectivity, navigation, meteorology, and exploration. CubeSats, low-cost mini-satellites, expand these capabilities by supporting Earth observation, remote communication, education, agriculture, and scientific research. They represent a breakthrough in space technology, fostering innovation, efficiency, and sustainable development.

This paper proposes an intelligent CubeSat-based framework with Blockchain integration to enhance the security of environmental monitoring. Unlike prior studies, it combines Artificial Neural Networks

(ANNs) to optimise connectivity, Deep Learning (DL) for object detection, and adaptive MIMO antennas for high data rates and reliability. Blockchain ensures secure communication between CubeSats and ground stations. The model is validated across four scenarios: water detection, tree counting, vegetation assessment, and oil spill monitoring. Although complexity is a challenge due to its hierarchical structure, modular design and mathematical modelling can improve efficiency. Overall, the framework offers a holistic advancement in secure, reliable environmental monitoring¹.

Figure 1 shows the proposed solution for environmental monitoring utilizes a two-segment system: a sky segment and a ground segment. The sky segment features a CubeSat equipped with various components, including an HD camera, sensors, and an adaptive MIMO antenna. The adaptive MIMO antenna enhances remote sensing by dynamically adjusting its radiation patterns, which optimise signal transmission and data rates. An intelligent DL algorithm, specifically YOLOv9, is integrated for object detection and analysis in high-precision aerial imaging. This CubeSat also uses the Normalised Difference Vegetation Index (NDVI) to assess vegetation health. The ground segment includes a Ground Control Station (GCS) that receives data from the CubeSat and manages its movement and energy. The GCS also collects data from ground sensors, and the communication link between the CubeSat and the GCS is secured using blockchain and optimised with ANNs.

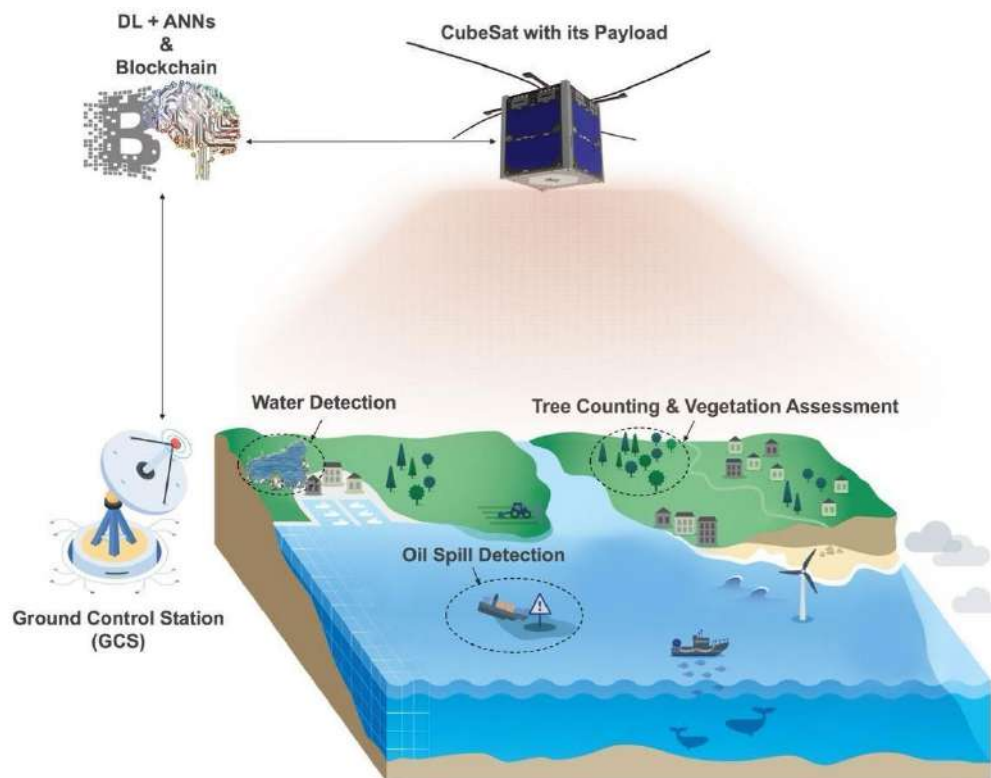


Figure 1: Conceptual outline of the proposed solution.

Figure 2 shows a flowchart of the proposed solution framework for environmental monitoring. The progress of the projection matrices for link budget, with which the ANNs (first brain) are initially

¹Faris A. Almalki, "Developing an Intelligent Framework with Blockchain Capabilities for Environmental Monitoring Using a CubeSat," *The Computer Journal* 68, no. 8 (2025): 968–84, <https://doi.org/10.1093/comjnl/bxaf017>

trained, are discrete events; while the progress of the projection matrix for the water detection, tree counting and vegetation assessment, and oil spill detection, with which the DL YOLOv9 (second brain) are trained, are considered as a continuous event as they evolve after each circle orbit.

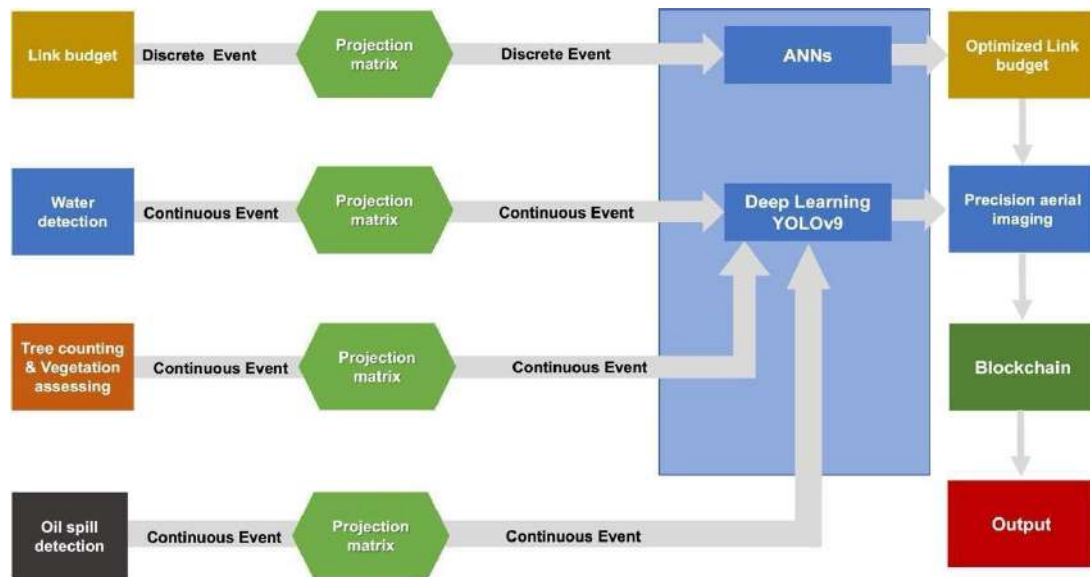


Figure 2: Detailed flowchart of the proposed framework solution.

Results and Discussion

This section shows a brief illustration of the simulation setup and results, which is a fundamental step to get early link budget predictions of the proposed CubeSat, before starting to build the CubeSat's prototype.

Figure 3 illustrates the CubeSat communication architecture using the satellite communications simulation toolbox in MATLAB. The toolbox includes functions to simulate, analyse, and visualise the CubeSat's dynamics and communications based on parameters and network configurations. Figure 4 shows the proposed antenna shape using a 4x4 microstrip patch MIMO antenna at a frequency of 28 GHz, using CST Microwave Studio, which consists of three layers: a ground layer of copper, a substrate layer of Rogers, and a patch layer of copper. These layers would help in improving the antenna's performance, reliability, and durability.

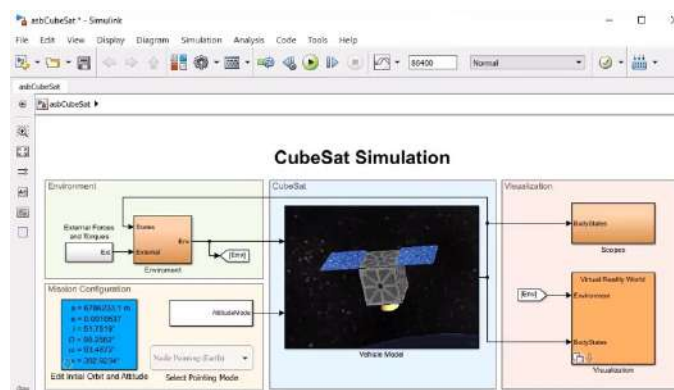


Figure 3: CubeSat network communication architecture.

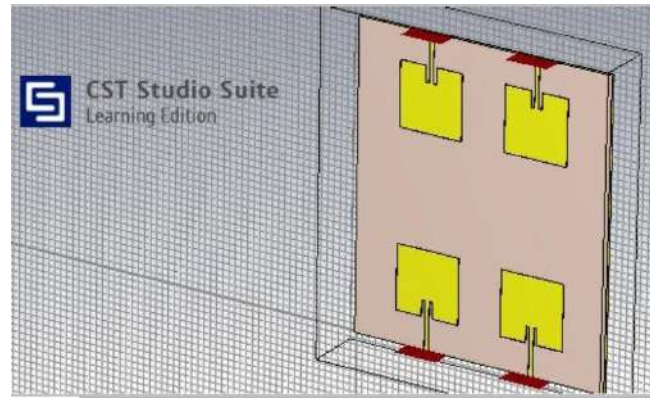


Figure 4: 4x4 microstrip patch MIMO antenna at a using CST toolbox.

An experiment was conducted on September 18, 2024, at Taif University, Saudi Arabia, using a CubeSat prototype. The prototype, as shown in Figure 5, was lifted to an altitude of 50 meters with a helium-filled tethered balloon. The CubeSat was equipped with an adaptive MIMO antenna, a camera, a GSM module for communication, and an AI framework that included ANNs and YOLOv9 models. The purpose of the experiment was to validate a sustainable environmental monitoring solution. The prototype was tested for four main tasks: water detection, tree counting, vegetation assessment, and oil spill detection.



a. CubeSat prototype with its payload.



b. CubeSat prototype with its payload.

Figure 5: The porotype implementation using a tethered balloon.

Graphs in Figure 6 show the implementation results when deploying the proposed solution for environmental monitoring. Figure 6a shows the water detection task, which is indicated by a green box, while the red one indicates that it is not a water body. The detection includes watersheds, water bodies, and their sizes, rather than their volumes. Figure 6b shows the tree counting task, where red boxes mean that the trees have been counted, while green box shows the latest recognition and counting. This can help in vast areas. Figure 6c shows the vegetation assessment task using NDVI, where squares with percentages show the NDVI results. The high percentage indicates that the plants are very healthy. Figure 6d shows the oil spill detection task, which shows the accuracy of detecting the oil substances against water.

The obtained results emphasise that the prototype demonstrates high accuracy in monitoring environmental surfaces such as water, forests, and farms in a cost-effective, rapid-deployment manner. These tasks would cover land and sea aspects, which give holistic environmental monitoring. To

precisely detect and monitor items in various environments, such as trees and water, bounding boxes must be applied within the proposed algorithm to improve performance and accuracy. These bounding boxes are a fundamental tool for defining and localising objects within a given space. They are essentially rectangular regions that enclose objects of interest, providing valuable information about their positions, sizes, and orientations.

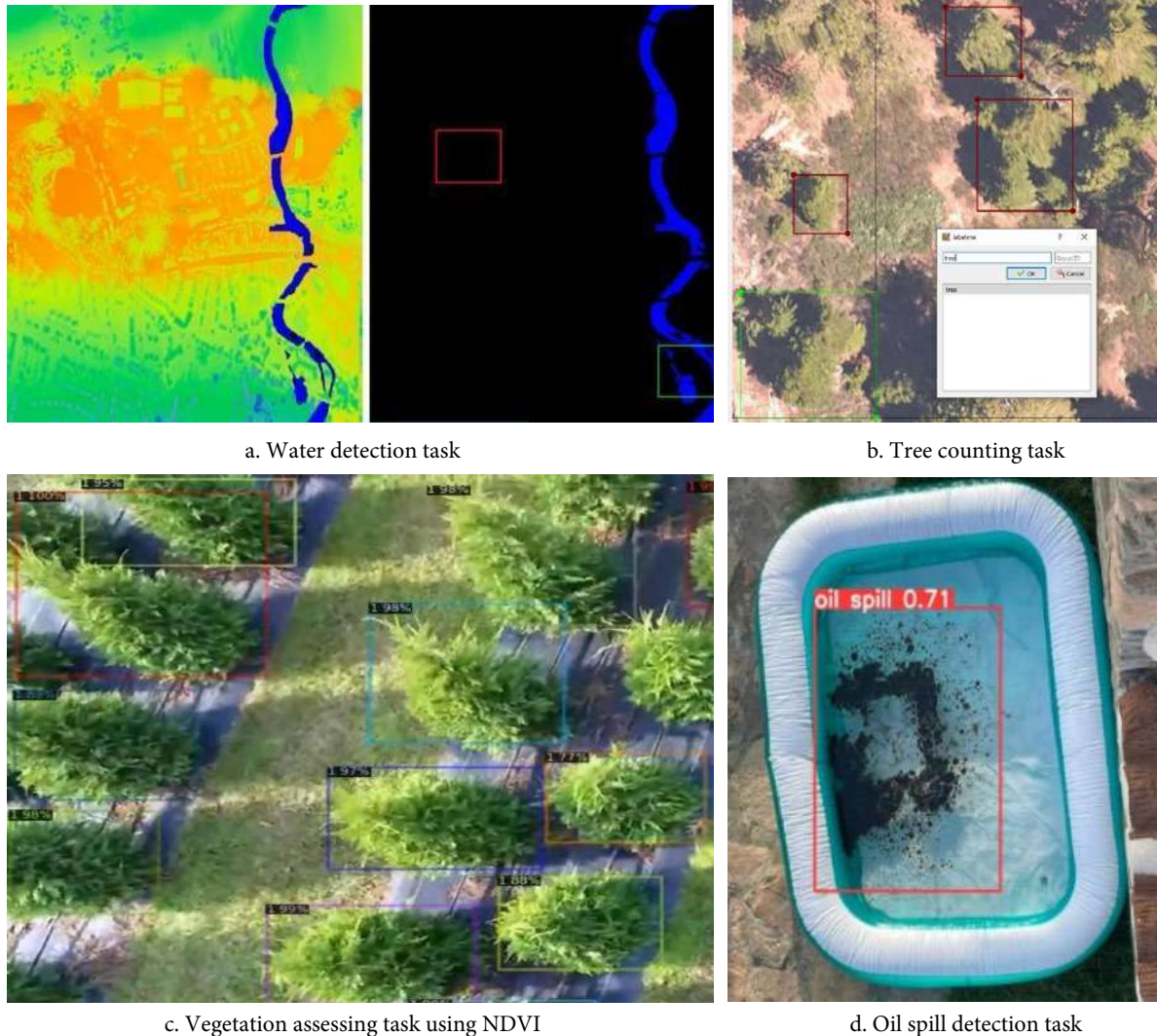


Figure 6: Implementation results of the proposed solution for environmental monitoring.

Graphs in Figure 7 show the performance of the 4x4 microstrip patch MIMO antenna. The graphs include indicators that evaluate the performance of the designed smart MIMO antenna includes S11, Voltage Standing Wave Ratio (VSWR), antenna gain, and antenna directivity. Overall results show that the S11 parameter, which evaluates impedance matching and efficient power transfer. A low S11 value, typically below -20 dBm, is desired for better performance and wider bandwidth. A VSWR of less than 2 is considered acceptable, as it reflects the efficiency of power transmission. Antenna gain and directivity are also measured, showing a focused radiation pattern that reduces power consumption and increases effective range with decent outcomes.

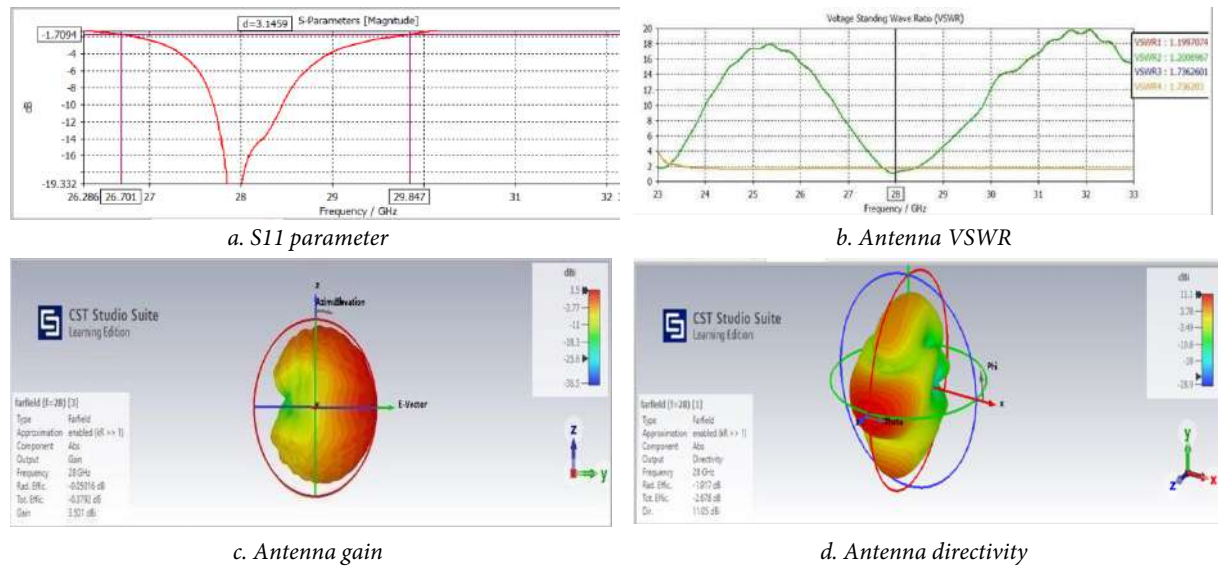


Figure 7: Performance of the 4x4 microstrip patch MIMO antenna.

Plots in Figure 8 show the link budget parameters. Using an optimisation technique, likely employing ANNs, the communication link's performance was significantly improved. The Received Signal Strength (RSS) increased from -74.05 dBm to -60.01 dBm, leading to more effective data reception. Path loss was reduced from 143.49 dB to 100 dB, enhancing communication quality across all distances. The Signal-to-Noise plus Interference Ratio (SNIR) improved from 8.23 dB to 5.02 dB, increasing signal strength relative to noise. Lastly, throughput rose from 30.06 Mb/S to 32 Mb/S, indicating faster data transfer. Overall, across all link budget parameters at an altitude of 400km, the optimised indicators are better than the non-optimised ones, which reflects improvement in the wireless network connectivity, coverage, and throughput.

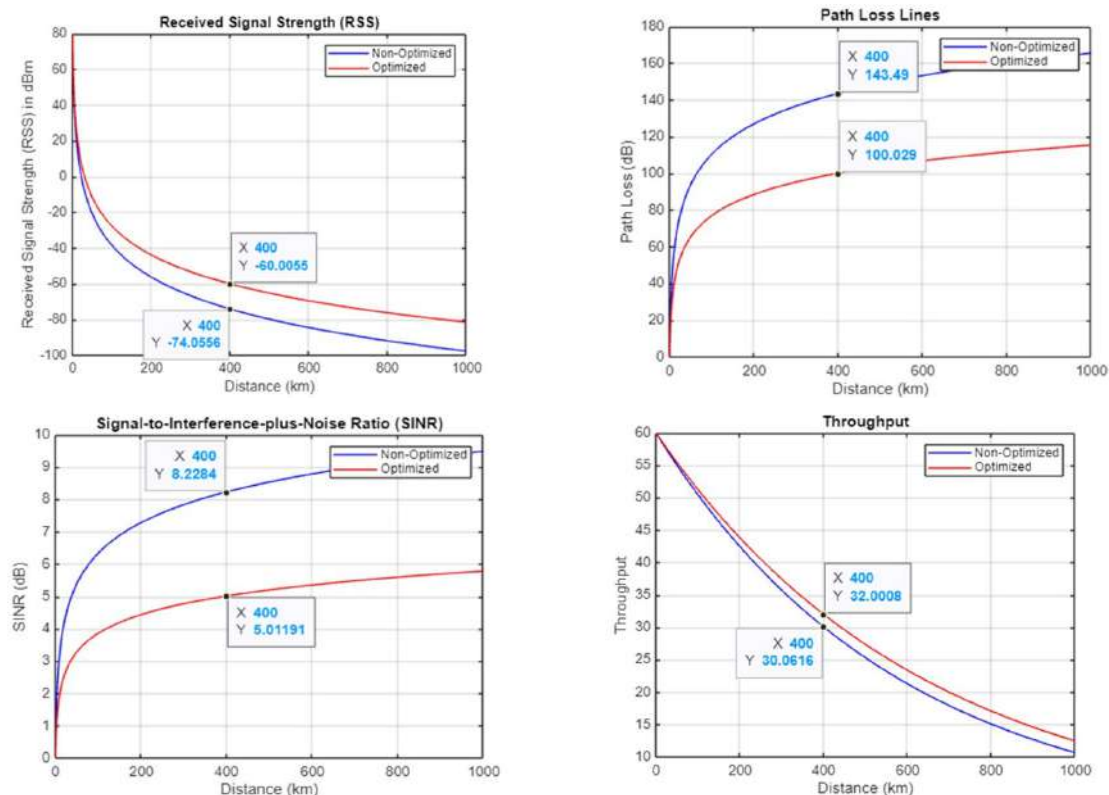


Figure 8: Link budget parameters in non- optimized and optimised scenarios.

Figure 9 shows that the ANN model achieved optimal performance at 192 epochs with a low Mean Squared Error (MSE), indicating good fitting. Training stopped at 193 epochs, showing no significant overfitting.

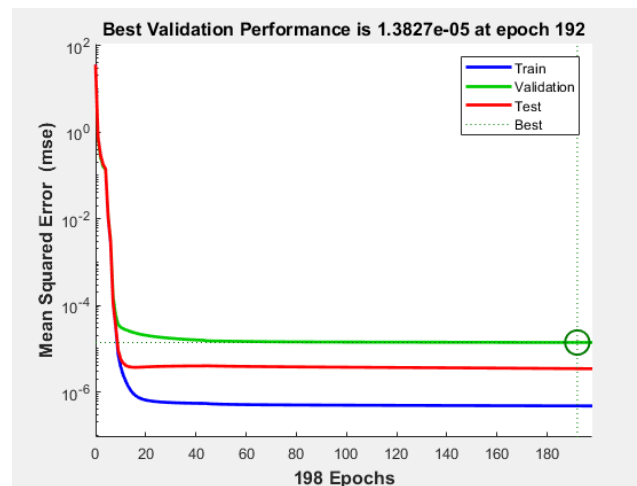


Figure 9: MSE performance of the ANN model.

Figure 10 shows the precision-recall curve of the YOLOv9 model. It serves as an evaluation of the performance of the object detection capability of the YOLOv9 model. The curve indicates a good predictive model with high accuracy, reaching 92%, since the precision stays high as the recall increases.

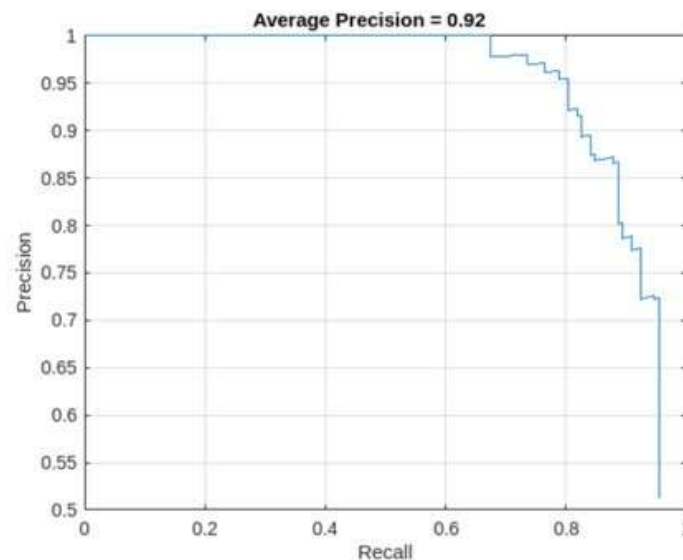


Figure 10: Precision-recall curve of the YOLOv9 model.

Blockchain performance can be analysed using key metrics like transaction prices, response times, block sizes, and the number of blocks. Figure 11 shows a framework in which transaction prices are influenced by market factors, such as Ethereum price volatility. Response times lengthen as network activity increases, reflecting throughput limitations. Block sizes expand with more transactions, posing scalability challenges and impacting processing latency. The number of blocks tracks network activity, indicating potential increases in orphan blocks under high throughput. Overall, the analysis reveals periods of stress on the network, highlighting areas for enhancement. CubeSat data is stored on IPFS, with its hash stored on a blockchain for integrity.

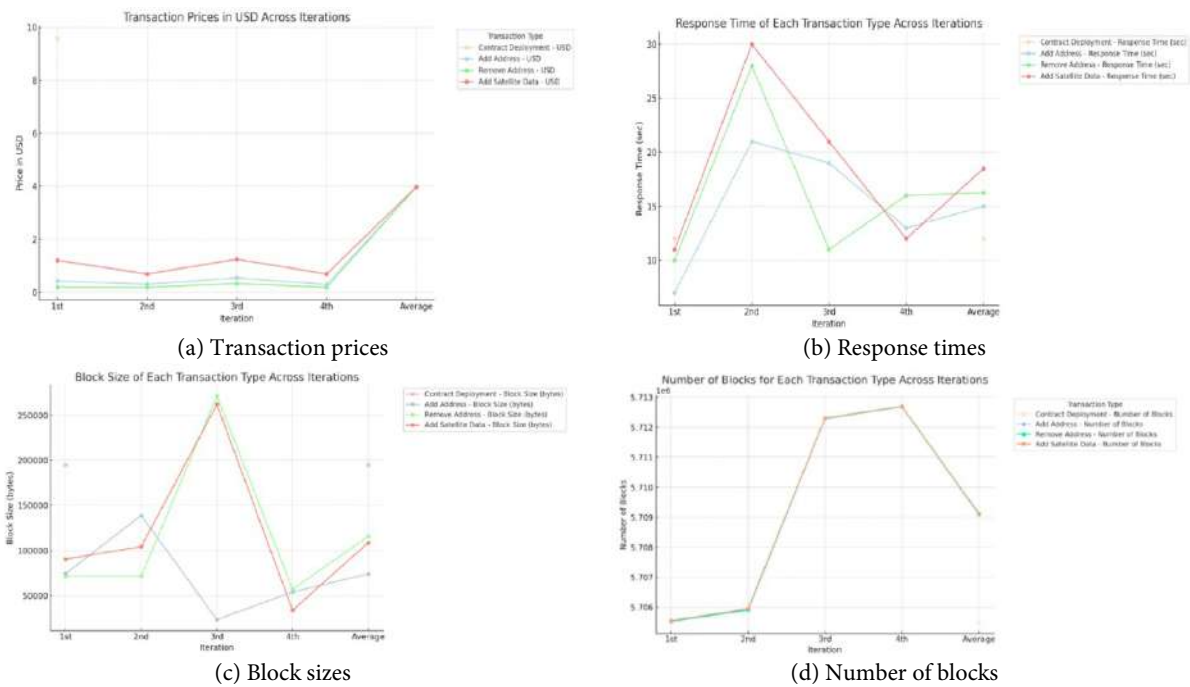


Figure 11: Performance indicators of Blockchain.

Conclusions

This work introduces an intelligent model integrated with a Blockchain framework for secure environmental monitoring using a CubeSat. The system utilises a CubeSat equipped with a camera and an adaptive MIMO antenna, complemented by ground-based IoT sensors. The solution was simulated and validated across four scenarios: water detection, tree counting, vegetation assessment, and oil spill detection. Blockchain technology ensures the security and integrity of data transmitted from the CubeSat to the ground station. The results demonstrate high accuracy in monitoring environmental surfaces with effective and rapid deployment. Future work includes potential CubeSat launches with space agencies and the development of a user-friendly data dashboard for analysis.

Acknowledgements

The author extends his appreciation to Taif University, Saudi Arabia, for supporting this work.

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Chapter 28

Simultaneous Selective Recovery of Lithium and Cobalt from Spent Lithium-ion Batteries Using Modified Bipolar Membrane Electrodialysis

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Abstract

The increasing use of lithium-ion batteries (LIBs) has led to significant volumes of battery waste and a growing demand for critical metals such as lithium (Li) and cobalt (Co). This study developed a selective electrodialysis process with bipolar membranes (EDBM) to simultaneously recover Li and Co from spent LIB cathode materials. Cobalt was converted into an anionic complex using a citric acid-based leaching system and hexacyanoferrate complexation, enabling its separation from Li under an applied potential. The optimised EDBM stack achieved recovery rates of >89% for Co and >93% for Li under a 25 mA cm⁻² current density. The recovered Li was obtained as high-purity lithium hydroxide (LiOH, >98%) and Co as cobalt hexacyanoferrate, which may be reused into battery-grade precursors. The process eliminated selective precipitation, significantly reducing the consumption of toxic reagents and minimising secondary waste generation. A preliminary economic analysis indicated a 28% reduction in operating costs compared to conventional hydrometallurgical routes, while life cycle analysis showed a 35% lower carbon footprint. This approach offers an energy-efficient, scalable, and environmentally benign alternative for battery metal recovery, enabling circular resource use in the LIB industry. The successful demonstration of this technology strengthens its viability for downstream industrial integration.

Keywords: *Lithium-ion Battery, Recycling, Bipolar Membrane Electrodialysis, Cobalt Recovery, Sustainable Hydrometallurgy*

Introduction

The rapid expansion of electric vehicle (EV) production and the escalating demand for lithium-ion batteries (LIBs) have created a pressing global need for sustainable recovery of critical raw materials, particularly lithium (Li⁺) and cobalt (Co²⁺). EV sales are projected to reach 43 million units by 2040¹, with end-of-life LIBs expected to generate over 11 million tons of waste by 2030². This waste stream presents not only an environmental concern but also a strategic opportunity, as spent LIBs are enriched

¹BloombergNEF, *Electric Vehicle Outlook 2024*, BloombergNEF, 2024 <https://about.bnef.com/electric-vehicle-outlook/>.

²International Energy Agency, *Global EV Outlook 2023*, IEA, 2023 <https://www.iea.org/reports/global-ev-outlook-2023>.

with lithium and cobalt, making them a viable secondary resource. Their efficient recovery is essential to advancing circular energy technologies, reducing reliance on virgin mining, and ensuring a stable material supply chain. Current industrial LIB recycling utilised pyrometallurgy, an energy-intensive and toxic process³, and hydrometallurgy, with large chemical consumption and high waste generation⁴. Electrochemical separation methods have emerged as a promising alternative that could overcome some limitations of traditional techniques. Electrodialysis (ED), in particular, is recognised as a ‘green’ separation technology that can selectively recover ions using electricity instead of added chemicals⁵. A recent study has applied ED to LIB recycling at laboratory scale, demonstrating that lithium can be efficiently separated from mixed-metal leachates given appropriate membranes and operating conditions⁶. Moreover, electrodialysis is a mature industrial technology and can be scaled by stacking membrane cell units, making it a promising candidate for industrial-scale LIB recycling⁷.

Bipolar membrane electrodialysis (EDBM) is a specialised form of electrodialysis that integrates water-splitting bipolar membranes into the stack. An EDBM stack allows direct generation of acid and base from a neutral salt feed solution. The ability to produce acid and base in situ is highly attractive for battery recycling. EDBM thus enables a closed-loop process with minimal external reagents. However, simultaneous recovery of lithium and cobalt via EDBM has not been extensively studied.

In this work, the simultaneous selective recovery of Li and Co from spent LIB cathode leach solution using an EDBM process was explored. Key technical innovations include using a chelating strategy and modifying membranes to facilitate selective and efficient transport, and the integration of acid/base regeneration within the electrodialysis cell.

Results and Discussion

Selective Separation Mechanism

The EDBM process here effectively enabled the simultaneous recovery of Li and Co from spent LIB cathode leachates. Using a citric acid-based leaching system combined with hexacyanoferrate complexation, cobalt was converted into a stable anionic complex, allowing it to migrate under an applied potential while Li^+ selectively passed through cation-exchange membranes. Li and Co exhibited significantly higher adsorption capacities (Figure 1a) than competing ions such as Ni^{2+} and Mn^{2+} , with Li^+ reaching $\sim 1.6 \text{ mmol g}^{-1}$ and $\text{Co}^{2+} \sim 1.3 \text{ mmol g}^{-1}$ after 30 min, while other ions remained below 0.2

³Brian Makuza et al., “Pyrometallurgical Options for Recycling Spent Lithium-Ion Batteries: A Comprehensive Review,” *Journal of Power Sources* 491 (2021): 229622 <https://doi.org/10.1016/j.jpowsour.2021.229622>.

⁴E. Asadi Dalini et al., “A Review on Environmental, Economic and Hydrometallurgical Processes of Recycling Spent Lithium-Ion Batteries,” *Mineral Processing and Extractive Metallurgy Review* 42 (2021): 628–651 <https://doi.org/10.1080/08827508.2020.1781628>.

⁵Alain Chagnes et al., “Lithium-Ion Battery Recycling: Metal Recovery from Electrolyte and Cathode Materials by Electrodialysis,” *Metals* 12, no. 11 (2022): 1859 <https://doi.org/10.3390/met12111859>.

⁶Soumaya Gmar et al., “Application of Electrodialysis for the Selective Lithium Extraction towards Cobalt, Nickel and Manganese from Leach Solutions Containing High Divalent Cations/Li Ratio,” *Recycling* 7, no. 2 (2022): 14 <https://doi.org/10.3390/recycling7020014>.

⁷Chagnes et al., “Lithium-Ion Battery Recycling,” 1859.

mmol g⁻¹. Correspondingly, high selectivity coefficients were observed (Figure 1b), with Li/Ni and Li/Mn ratios exceeding 200, and Co/Ni and Co/Mn also rising steadily over time, confirming strong preferential separation of Li⁺ and Co²⁺ over competing species. The recovered product streams achieved high purity (Figure 1c), with lithium hydroxide (LiOH) exceeding 98% and cobalt purity approaching 98% within 30 min of electrodialysis. Energy demand was modest (Figure 1d), with specific energy consumption stabilising at ~3.2 Wh L⁻¹, equivalent to ~0.7–0.9 kWh kg⁻¹ Li, which is comparable to reported values for similar electrodialysis systems⁸. The optimised five-unit EDBM stack (Figure 2) operated at 25 mA cm⁻², achieving recovery rates of >93% for Li and >89% for Co. Li was recovered as LiOH (>98%), while cobalt was precipitated as cobalt hexacyanoferrate, both suitable for reuse as cathode precursors.

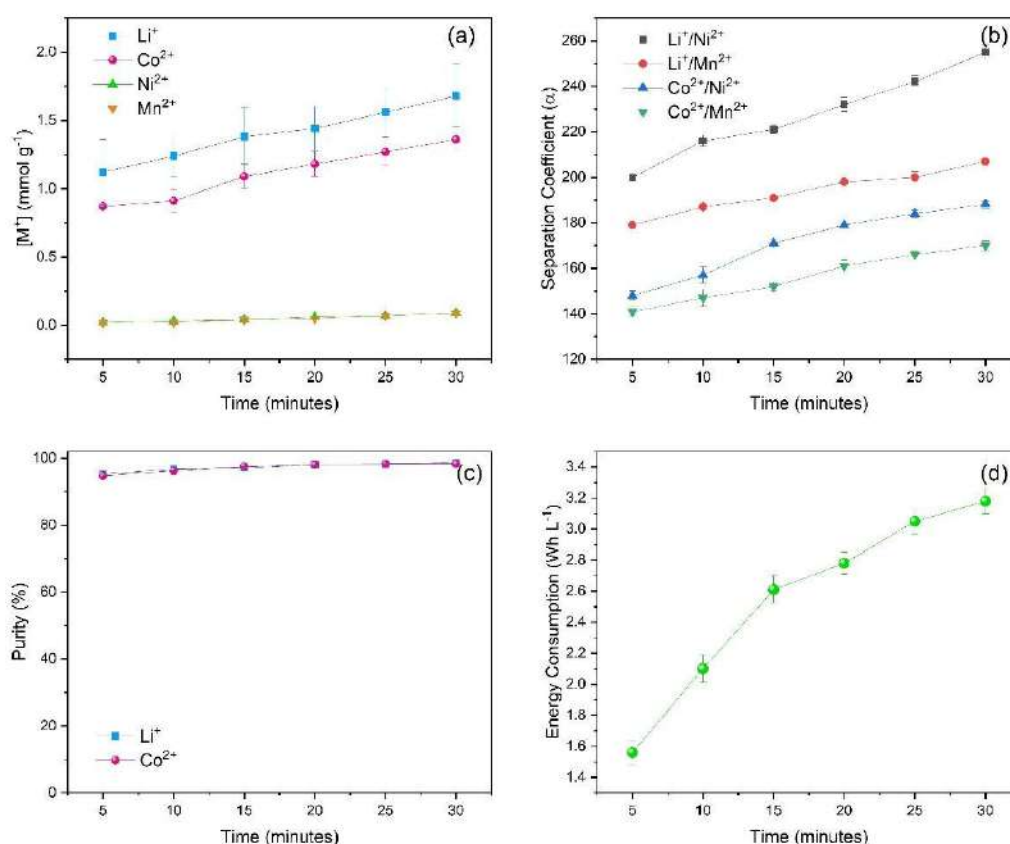


Figure 1: (a) Adsorption capacity of Li⁺ and Co²⁺ vs. other metal ions (Ni²⁺, Mn²⁺) on the modified membranes over time, (b) corresponding selectivity coefficients (Li/M, Co/M), (c) purity of recovered Li and Co as a function of electrodialysis time, (d) specific energy consumption of the EDBM process over time.

Figure 2 further illustrates the mechanism by which the EDBM process achieves this dual recovery. Cobalt complexed as hexacyanoferrate migrated through the modified anion-exchange membranes into the anode compartment, while Li⁺ selectively traversed the modified cation-exchange membranes into the cathode compartment, where hydroxide ions generated by the bipolar membranes combined to form LiOH. This integrated configuration simultaneously produced high-purity LiOH and cobalt

⁸Adam Isaksson et al., “Zero-Waste Recycling of Lithium and Cobalt from Lithium-Ion Batteries by Three-Stage Electrodialysis,” *Separation and Purification Technology* 368 (2025): 133060
<https://doi.org/10.1016/j.seppur.2025.133060>.

hexacyanoferrate, effectively performing two separations in a single unit operation. The process reduced chemical inputs and secondary waste by eliminating the multiple neutralisation and precipitation steps required in conventional hydrometallurgical flowsheets.

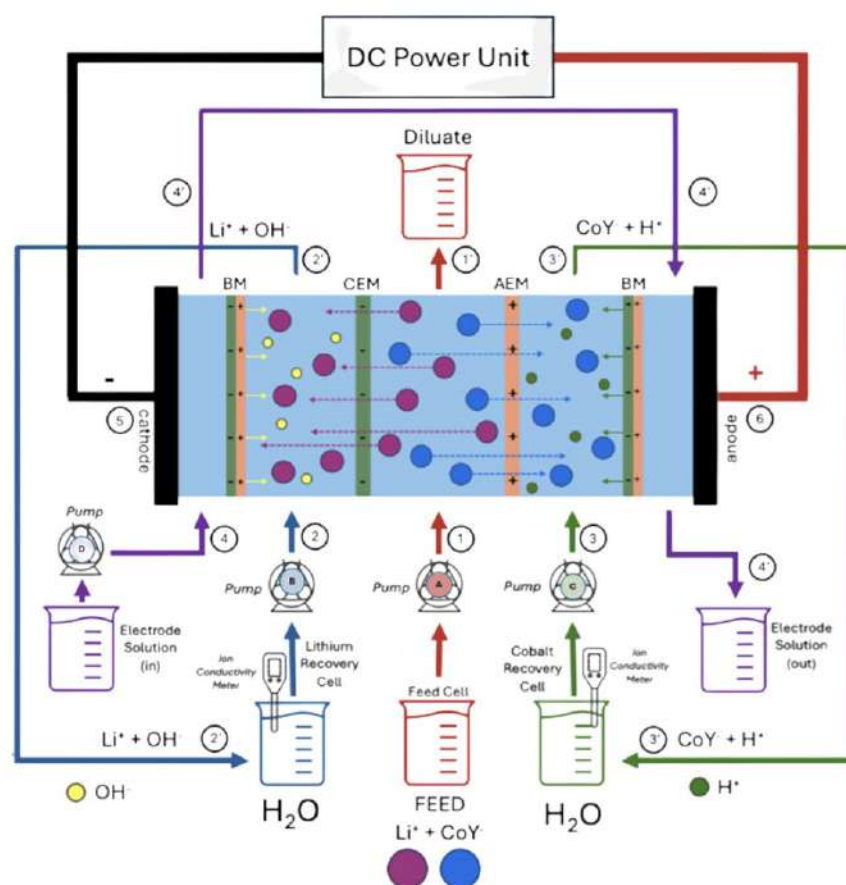


Figure 2: Schematic illustration of the bipolar membrane electrodesialysis (EDBM) process for simultaneous Li and Co recovery.

Energy Consumption

An energy consumption was calculated from the electrical input required to drive ion transport and water dissociation in the EDBM stack, using $E = (V \times I \times t)/m$, where V is cell voltage, I is current, t is operation time, and m is the mass of lithium recovered. This gave a specific energy consumption of $\sim 0.7\text{--}0.9$ kWh per kg of Li, lower than reported ranges of $1\text{--}2$ kWh kg⁻¹⁹ for similar systems, and close to the 1.33 kWh kg⁻¹ achieved with redox-mediated EDBM¹⁰. In contrast, the 35% smaller carbon footprint was determined by life cycle analysis (LCA) comparing EDBM to hydrometallurgy. Conventional processes incur high emissions from large-scale acid/base production, neutralisation reactions, and waste treatment. In EDBM, acid and base are regenerated in-situ, chemical use is minimised, and the main input is electricity, which can be partly renewable. Accounting for avoided

⁹Jie Yan et al., "Selective Electrodialysis with Bipolar Membranes for Cobalt and Lithium Recovery from Spent Lithium-Ion Batteries," *AIChE Journal* (2025, early view) <https://doi.org/10.1002/aic.18786>.

¹⁰Jeon et al., "Chemical Free pH Control for Efficient Lithium Recovery via Redox-Couple Mediated Bipolar Membrane Electrodialysis." *Desalination*, 603 (2025): 119145.

reagent production and reduced waste, the LCA showed that EDBM achieved a carbon footprint reduction of about one-third relative to conventional methods. The LCA used a cradle-to-gate boundary with inventories from Ecoinvent v3.9.1, analysed in openLCA 1.11 via ReCiPe 2016 Midpoint (H) and cross-checked against IPCC 2021 GWP factors.

Economic and Environmental Analysis

The EDBM process replaces most chemical reagents with electricity, which, though not cost-free, is modest in demand ($<1 \text{ kWh kg}^{-1} \text{ Li}$) and can be supplied by renewables. Unlike hydrometallurgical routes that consume large volumes of acids, bases, and solvents, producing tonnes of neutralised salts for disposal, EDBM regenerates its acid and base in situ, leaving only minor consumables such as recyclable hexacyanoferrate and water. The advantages are high-purity LiOH and Co recovery, very low waste, and reduced CO_2 footprint. A preliminary economic analysis indicated a 28% reduction in operating costs, largely due to lower reagent consumption, while an LCA showed a 35% smaller carbon footprint compared to conventional processes. Although membranes represent the main capital cost, their multi-year lifespan offsets recurring chemical expenses typical of hydrometallurgy. Moreover, eliminating neutralisation preserves reagent value and avoids secondary waste. When powered by renewable energy, the environmental benefits are amplified, making EDBM a closed-loop, greener, and economically competitive route for LIB recycling.

Conclusions

EDBM with the tailored as-prepared molecularly imprinted membranes has been shown to recover Li and Co from spent lithium-ion battery leachate with high efficiency and selectivity, producing $>99\%$ purity LiOH and achieving $>90\%$ recovery of both metals in under 30 min with negligible cross-contamination. By integrating hexacyanoferrate-assisted complexation in the electrochemical system, the process overcomes the co-extraction issues of conventional methods. Key advantages include minimised chemical use through in-situ acid and base generation, moderate electricity demand ($<1 \text{ kWh kg}^{-1} \text{ Li}$), direct production of battery-grade LiOH, regeneration of leaching agents, reduced greenhouse gas emissions and waste streams, and scalability through modular electrodialysis stacks. As a technically robust, energy-efficient, and environmentally benign alternative, EDBM has a strong potential for industrial adoption, either as a standalone process or as part of integrated recycling flowsheets, advancing sustainable and circular management of LIB materials.

Acknowledgment

The authors acknowledge that this work was funded by the Philippine Department of Science and Technology (DOST).

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Chapter 29

Advancing Circular Economy Through Ad-tech for Optimising Future Manufacturing

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Abstract

The proposed research explores the intersection of Ad-tech, predictive analytics, and circular economy (CE) principles to support manufacturers in transitioning to circular models. Our method introduces a digital platform that enables data-driven circular manufacturing by embedding consumer engagement strategies, behavioural analytics, and supply chain integration to close resource loops, extend product lifecycles, and reduce waste. The research aligns with Industry 5.0 and the United Nations Sustainable Development Goals and focuses on three key objectives: (1) enhancing resource efficiency using life cycle assessment (LCA) tools and real-time inventory monitoring, (2) promoting sustainable consumer behaviours through personalised Ad-tech, and (3) enabling cross-sectoral collaboration for reuse and recovery.

Keywords: *Circular Economy (CE), Ad-Tech & Consumer Engagement, Predictive Analytics, Data-Driven Manufacturing*

Introduction

The urgency of transitioning toward circular economy (CE) practices in manufacturing has grown significantly in response to the escalating climate crisis, resource depletion, and the inefficiencies of linear production models. CE frameworks promise to reduce waste, conserve raw materials, and enable sustainable growth through continuous reuse, recycling, and regeneration of products and resources. However, despite increasing attention, many brands and manufacturers struggle to adopt CE principles effectively due to operational constraints, limited consumer engagement, and a lack of scalable data infrastructure.

Digital transformation in manufacturing has introduced tools that enable greater automation, traceability, and efficiency. Yet these tools often have a narrow focus on supply chain or production improvements without integrating the behavioural dimension, necessary to close resource loops effectively. This research proposes a novel approach that incorporates Ad-tech strategies—traditionally used in consumer marketing—to bridge this gap. By embedding behavioural insights into predictive analytics and resource recovery, manufacturers can both optimise internal operations and influence external consumption patterns.

The proposed platform explores how these interdisciplinary technologies can facilitate systemic change in manufacturing by enabling dynamic inventory tracking, forecasting product return likelihood, and

nudging consumers toward sustainable behaviours. This paper outlines the foundational methods and early-stage findings that validate this model and sets the stage for future scalable adoption in the industry.

Background and Motivation

Manufacturers have long operated within a linear system of take-make-dispose, resulting in significant environmental and economic inefficiencies. In contrast, the circular economy model emphasises longevity, reuse, and regeneration. Yet the transition to CE has been slow due to challenges such as fragmented supply chains, underdeveloped data ecosystems, and low consumer participation in take-back or reuse programs.

Ad-tech platforms, known for their data-driven precision and personalization, offer a unique lens through which one can reimagine circular supply chains. These systems already track user behavior, preferences, and real-time feedback loops. When redirected toward sustainability goals, they can drive consumer participation in recycling, repair, and remanufacturing initiatives.

Furthermore, governments and institutions are pressurising on industries to adopt sustainable practices. Global initiatives such as the United Nations Sustainable Development Goals (SDGs), Industry 5.0 frameworks, and enforcement of regulations like Section 1557 of the Affordable Care Act create both the imperative and opportunity for innovation.

Verifiable Evidence Supporting Platform Claims

- **Behavioural AdTech Personalization:**

Research shows that behavioural targeting and personalization significantly improve consumer engagement and conversion outcomes. Industry analysis indicates that 71% of consumers expect personalized interactions, while 76% express frustration when content is not tailored to their preferences.¹ Additionally, large-scale advertising studies demonstrate that targeted campaigns can substantially outperform non-targeted approaches in both click-through rates and revenue generation.² These findings support the feasibility of leveraging AdTech to deliver sustainability-focused messaging to environmentally conscious consumers.

- **Circular metrics in marketing:**

Evidence from circular economy research indicates that consumers are more likely to select products when circular attributes—such as recyclability, durability, and reuse potential—are clearly communicated.³ This suggests that integrating circular performance indicators into

¹Anstine, “Consumer Acceptance of Products Made from Recycled Materials: A Scoping Review.” *Resources, Conservation & Recycling*, 186 (2000): 106533.

<https://doi.org/10.1016/j.resconrec.2022.106533>

²McKinsey & Company, “The Value of Getting Personalization Right—or Wrong—Is Multiplying,” 2022. Accessed June 30, 2025, <https://www.mckinsey.com>.

³BlueLithium (Yahoo! Advertising), “Study on Behavioral Targeting: 400 Million Impressions,” 2006. Accessed June 30, 2025, <https://www.yahooinc.com>.

marketing and advertising metrics can meaningfully influence purchasing decisions, reinforcing the role of data-driven communication in advancing circular consumption.

- **Consumer demand and feedback loops:**

Emerging research on digital engagement and advertising transparency demonstrates that consumer response is highly sensitive to how personalization is implemented. Studies show that acceptable and transparent targeting increases engagement, while overly intrusive or “creepy” personalization reduces effectiveness.⁴ This highlights the importance of ethical, user-centered AdTech strategies in building trust and enabling feedback-driven systems, which are critical for supporting demand-driven manufacturing and continuous product lifecycle optimization.

- Harvard Business School research (as featured in *Wired*) demonstrates that transparency in acceptable targeting increases engagement, while “creepy” approaches dampen response.

Method

This combines life-cycle assessment (LCA) tools, real-time inventory data, and Ad-tech-inspired predictive analytics to create a robust and scalable digital platform for circular manufacturing. The development of the platform followed an iterative prototyping model and simulated behavioural scenarios to evaluate the system's effectiveness.

First, LCA frameworks such as openLCA were integrated into the platform to map environmental impacts across each stage of the product lifecycle—from raw material sourcing to end-of-life. This enabled precise visibility into carbon emissions, water usage, and material depletion, allowing manufacturers to quantify benefits of circular actions.

Second, real-time inventory data were modelled to simulate how dynamic stock updates and product tracking could trigger reminders or incentives for product returns and repairs.

Third, predictive analytics and consumer segmentation algorithms were built on synthetic behavioural data, designed to mimic real-world engagement patterns. These models aimed to forecast the likelihood of sustainable actions, such as opting into take-back programs based on previous behaviour, demographics, and environmental values.

Platform-app Interconnection

The **AdTech engine** serves as the backend brain:

- It collects user data from the app and digital product IDs
- Feeds it into segmentation + targeting models
- Pushes campaigns across ad channels (Facebook, TikTok, in-app banners, email, etc.)
- Tracks return behaviour, A/B ad performance, sustainability KPIs, and user-level impact.

⁴Ellen MacArthur Foundation and Circle Economy, “The Importance of Circular Attributes for Consumer Choice of Fashion Products,” *Journal of Cleaner Production*, (2024), Accessed June 30, 2025, <https://www.sciencedirect.com>.

Product: Wearable Tech Jacket (Fashion + Electronics)

A smart jacket that tracks activity and integrates with circular care/return services.

Circular Model:

- Built-in sensor module can be removed and reused
- Fabric recycled or remade by brand partner
- Subscription model for upgrades or seasonal swaps

AdTech Integration:

- Push ads for module upgrade after 6 months
- Ads for free return kit once jacket wear reaches threshold
- Partnership campaigns: “Recycle jacket, get 3 months of Spotify Premium” (Figure 1).

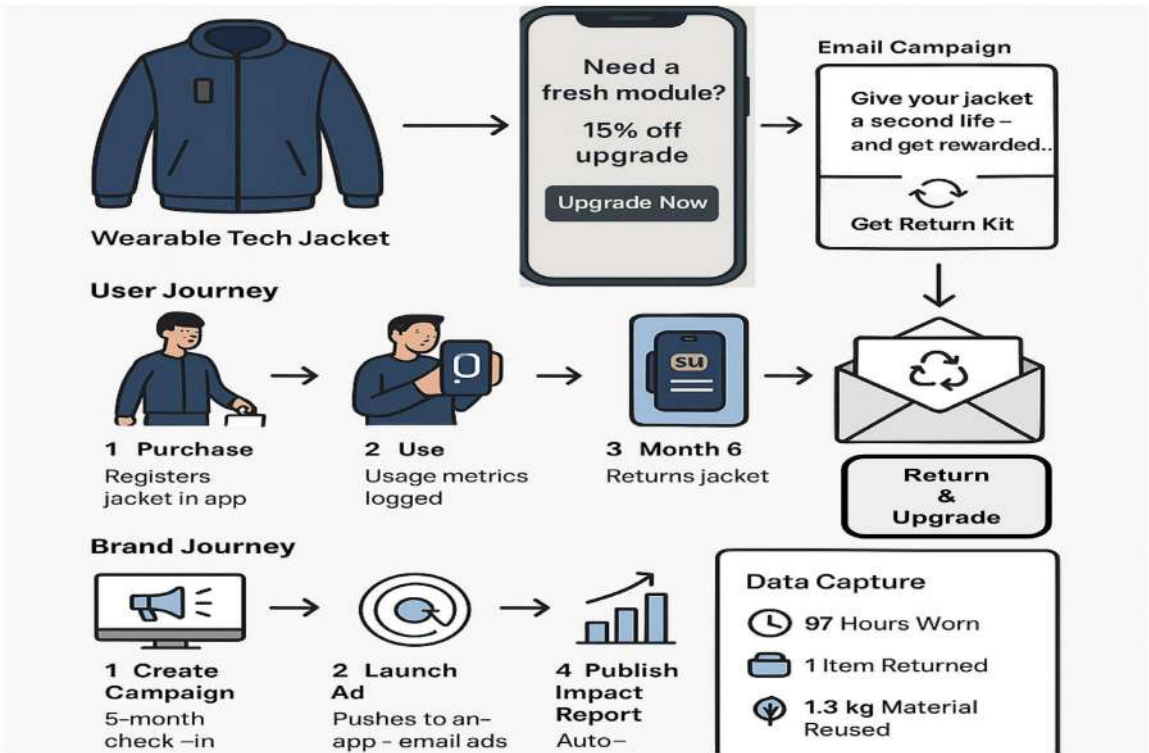


Figure 1: Wearable Tech Jacket with circular care/return services (User Journey + Brand Journey)

Prototype Journey (User + Brand Interaction)

Step	Action	Trigger	AdTech Role
Purchase	User buys jacket (in-store or online)	Digital product ID is activated	Registers jacket through the app
Use	Jacket tracks activity, time-worn	Usage metrics logged	Lifecycle segmentation begins
Month	Jacket has seen heavy use	>80 wear hours logged	App shows: ‘Need a fresh module? 15% off upgrade’
Month	Fabric shows signs of wear	Based on smart textile diagnostics	Push: ‘Return your jacket and get a \$40 voucher’
Return	User initiates return	QR code scan → shipment label	Brand logs impact (CO ₂ saved, fabric reclaimed)

Step	Action	Trigger	AdTech Role
Reward	User receives loyalty points	Verified return	Dynamic ad offers a new colour version or accessory

User Journey (Individual App)

Prototype Journey (Brand Interaction)

Finally, messaging engines, borrowed from Ad-tech, were configured to test personalised consumer nudges through simulated A/B testing. For example, consumers classified as ‘early adopters’ of sustainable behaviour received targeted content designed to reinforce recycling habits.

Step	Action	AdTech Input	Outcome
Creat campaign	‘6-month check-in’ campaign for core module upgrade	Lifecycle cohort: 1500 users	Geo-filters applied (NYC + LA)
Launch Ad	Pushes to in-app + Meta ads + email	Dynamic content: Module still under warranty vs expired	Real-time A/B test of conversion copy
Track return rate	Monitor 30-day engagement	Usage vs return correlation	Optimise ad cadence for next release
Publish impact report	‘Customers returned 63% of jackets before 9 months’	Auto-generated data from platform	Improves ESG marketing credibility

Brand Journey (Company Dashboard)

Methods

To assess the potential impact of the proposed AdTech-powered circular economy platform, a rule-based behavioural simulation was conducted modeling 10,000 user journeys through the lifecycle of a wearable tech jacket. Users were segmented by both behavioural engagement (e.g., passive and eco-motivated) and by product price tier (low, mid, high). Simulated platform interventions included predictive nudging ads, lifecycle-based personalization, and in-app sustainability prompts tied to the jacket's digital ID.

Each price tier influenced behavioural assumptions:

- **Low-cost products** (< \$100) were associated with lower return and repair motivation, requiring stronger incentives.
- **Mid-priced products** (\$100–\$250) exhibited the highest response rates to lifecycle ads and circular campaigns.
- **High-cost products** (> \$300) triggered longer ownership periods and higher repair engagement, though return frequency was lower.

Behavioural triggers were informed by data benchmarks from platforms, such as Patagonia Worn Wear, Loop by TerraCycle, and Fairphone, as well as standard AdTech performance metrics (e.g., dynamic ad CTRs, email open/click-through rates). Circularity outcomes, such as material recovery, lifecycle extension, and manufacturing waste reduction, were extrapolated based on user actions and mapped

against closed-loop system assumptions. This multi-dimensional simulation illustrates the platform's efficacy across different economic product categories.

Finally, the project establishes a technical blueprint for how marketing and operational technologies can converge to solve sustainability challenges. Unlike traditional CE tools that focus solely on materials, this approach emphasises behavioural and informational dynamics^{5,6}.

Results and Discussion

The platform was evaluated using early-stage simulations across synthetic product and consumer datasets. Initial findings support the hypothesis that an integrated CE-Ad-tech framework can deliver measurable improvements in resource efficiency and behaviour change (Figure 2).



Figure 2: Description of User + Brand Interaction.

Conclusion

This chapter proposes and validates a new paradigm for circular manufacturing that integrates Ad-tech, predictive analytics, and lifecycle analysis to deliver measurable environmental and operational gains. Early-stage validation of the proposed platform suggests strong potential to reduce waste, improve resource recovery, and change consumer behaviour through personalization and feedback loops.

⁵Kim, Tami, et al., "Online Ad Targeting Works—As Long as It's Not Creepy," *Wired*, 2018. Accessed June 30, 2025, <https://www.wired.com>.

⁶Reis, Joe and Matt Housley, *Fundamentals of Data Engineering: Plan and Build Robust Data Systems*, (Sebastopol, CA: O'Reilly Media, 2022), [https://soclbrary.futa.edu.ng/books/Fundamentals%20of%20Data%20Engineering%20\(Reis,%20JoeHousley,%20Matt\)%20\(Z-Library\).pdf](https://soclbrary.futa.edu.ng/books/Fundamentals%20of%20Data%20Engineering%20(Reis,%20JoeHousley,%20Matt)%20(Z-Library).pdf).

By leveraging tools traditionally used in marketing and repurposing them for sustainable consumption, the platform enables a proactive, data-driven shift in how manufacturers design and deliver products. It goes beyond compliance to create business value and environmental resilience. The approach also aligns with emerging standards for responsible AI and green supply chains.

Future research will focus on implementing real-world pilots in sectors such as electronics and healthcare, integrating ESG reporting standards, and exploring partnerships with recycling logistics providers. The ultimate vision is to create a cross-sector, interoperable infrastructure that accelerates the global transition to circular economy manufacturing models.

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Chapter 30

Transesterification Optimization of Vhembe Macadamia Nuts Oil into Biodiesel Using Inorganic KOH Catalyst

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Abstract

This study investigates the optimization of biodiesel production from macadamia nut oil (MNO) using potassium hydroxide (KOH) catalyst and methanol via transesterification. Response Surface Methodology (RSM) with a Box–Behnken design (BBD) was applied to optimize the influence of reaction temperature, alcohol-to-oil molar ratio, and catalyst weight on biodiesel yield. Experimental results showed that optimal conditions (alcohol-to-oil ratio of 6:1, temperature of 60 °C, and 1 wt.% catalyst) produced a maximum yield of 91%. Physicochemical analysis revealed that the properties of the biodiesel, including viscosity, flash point, and cetane number, met ASTM D6751 specifications, confirming successful transesterification. Gas chromatography–mass spectrometry (GC-MS) and Fourier transform infrared spectroscopy (FTIR) further validated the conversion of macadamia nut oil to biodiesel. The findings highlight the potential of macadamia nut oil as a viable feedstock for sustainable biodiesel production.

Keywords: *Macadamia nut oil, KOH catalyst, Methanol, Biodiesel, Physicochemical properties, Reaction parameters*

Introduction

The global transition towards sustainable energy is driven by increasing energy demand, climate change concerns, and the depletion of fossil fuel reserves. Fossil-based diesel remains the dominant transportation fuel worldwide, yet its contribution to greenhouse gas emissions and dependency on finite resources highlights the urgent need for renewable alternatives. Biodiesel has therefore emerged as a promising renewable substitute due to its biodegradability, non-toxic nature, reduced exhaust emissions, and compatibility with conventional diesel engines¹. Over the past two decades, research has

¹L. C. Meher, et al., “Technical Aspects of Biodiesel Production by Transesterification - A Review,” *Renewable and Sustainable Energy Reviews*, 10, no. 3 (2006): 248–268, <https://doi.org/10.1016/j.rser.2004.09.002>.

focused on exploring diverse feedstocks such as vegetable oils, animal fats, and waste cooking oils for biodiesel production. However, issues such as feedstock cost, competition with food sources, and variable physicochemical properties remain challenges in scaling up biodiesel.

South Africa presents unique opportunities for biodiesel development due to its rich agricultural base, large rural economy, and government policies that encourage renewable energy policies. One underutilized yet abundant agricultural product is macadamia nut oil (MNO), particularly in Limpopo Province where macadamia farming is well established. Unlike staple oilseeds, macadamia is not a major dietary component, and non-premium nuts and processing by-products can be utilized, minimizing competition with food resources. MNO's high oleic acid content makes it chemically stable and suitable for transesterification². Furthermore, the potential for scaling production through continuous reactor systems and modular plant designs supports high-throughput processing and decentralized energy generation. This study investigates the optimization of biodiesel production from MNO using potassium hydroxide (KOH) catalyst and evaluates the fuel properties of the resulting biodiesel against international standards.

Materials and Methods

Macadamia nuts were sourced from Tshakhuma market in Limpopo Province. The oil was extracted using Soxhlet extraction with n-hexane as solvent. In practice, the Soxhlet method provides high extraction efficiency since it continuously washes the biomass with hot solvent, ensuring near-complete recovery of oil. The extraction process typically lasted six hours with a solvent-to-nut ratio of 10:1, producing a golden-yellow oil that was subsequently dried to remove residual solvent.

The transesterification reactions were carried out with methanol and inorganic KOH catalyst under varying alcohol-to-oil molar ratios (2:1–12:1), temperatures (50–70°C), and catalyst loads (1–5 wt.%). The significance of alcohol-to-oil molar ratios in driving transesterification forward has been emphasized in prior studies, since excess alcohol improves reaction completion but may complicate separation³. To optimise the combined influence of these factors, Response Surface Methodology (RSM) was applied using a Box–Behnken Design (BBD). This statistical design is widely employed because it requires fewer experimental runs compared to central composite designs while still allowing robust modeling of quadratic interactions⁴.

Characterization of MNO and biodiesel was conducted following ASTM D6751 standards, including density, viscosity, flash point, and cetane number. The chemical conversion was confirmed using gas

²Sandra L.B. Navarro & Christianne E.C. Rodrigues, "Macadamia oil extraction methods and uses for the defatted meal byproduct", *Trends in Food Science & Technology*, 54, (2016): 148-154, <https://doi.org/10.1016/j.tifs.2016.04.001>.

³Musa, Atadashi, "The effects of alcohol to oil molar ratios and the type of alcohol on biodiesel production using transesterification process," *Egyptian Journal of Petroleum* 25 (2016): 21–31, <https://doi.org/10.1016/j.ejpe.2015.06.007>.

⁴Aworanti et al., "Statistical Optimization of Process Variables for Biodiesel Production from Waste Cooking Oil Using Heterogeneous Base Catalyst", *British Biotechnology Journal*, 3, no. 2, (2013): 116-132, <http://doi.org/10.9734/bbj/2013/1381>.

chromatography–mass spectrometry (GC-MS) to identify fatty acid methyl esters, and Fourier transform infrared spectroscopy (FTIR) to detect ester functional groups. These techniques provide complementary evidence, with GC-MS offering detailed compositional data and FTIR rapidly confirming chemical bond transformations⁵.

The design parameters used are summarized in Table 1.

Table 1: The experimental design parameters.

Factor	Unit	Level	
		Low	High
Alcohol: Oil ratio	Mol	2:1	12:1
Temperature	°C	50	70
Catalyst Amount	wt. %	1	5

Results and Discussion

Optimal biodiesel yield of 91% was obtained at 6:1 alcohol-to-oil molar ratio, 60 °C, and 1 wt.% KOH catalyst. This compares favourably with studies on other feedstocks, such as parsley seed oil⁶ and flaxseed oil⁷ which reported yields in the range of 85–90% under optimized conditions. The high yield from macadamia nut oil underscores its potential as a robust feedstock. Yields decreased at higher alcohol ratios (e.g., 12:1) and higher catalyst loads, likely due to soap formation and reverse reactions, consistent with findings reported by Musa Atadash³, shows the detailed biodiesel yields under different conditions are presented in Table 2, while the experimental setup and model validation are shown in Figure 1 and Figure 2⁸.

Table 2: Biodiesel yield under different conditions.

Runs #	Factor A	Factor B	Factor C	Response
	Oil: Alcohol Molar Ratio (Mol)	Temperature (°C)	Catalyst Weight (wt. %)	Biodiesel Yield (%)
1	12	60	1	78
2	6	70	3	69
3	6	50	3	70
4	6	60	5	76
5	9	60	3	76
6	9	60	3	78

⁵M. A. Dubé, et al., “A Comparison of Attenuated Total Reflectance-FTIR Spectroscopy and GPC for Monitoring Biodiesel Production,” *Journal of the American Oil Chemists’ Society*, 81, no. 6 (2004): 599–603, <https://doi.org/10.1007/s11746-006-0948-x>.

⁶S. O. Bitire, et al., “Production and optimization of biodiesel from parsley seed oil using KOH as catalyst for automobiles technology,” *International Journal of Advanced Manufacturing Technology*, 116 (2021): 315–329, <https://doi.org/10.1007/s00170-021-07415-6>.

⁷M. Danish, et al., “Optimization of process variables for biodiesel production by transesterification of flaxseed oil and produced biodiesel characterizations,” *Renewable Energy*, 139 (2019): 1272–1280, <https://DOI:10.1016/j.renene.2019.03.036>.

⁸Bitire, et al., “Production and Optimization,” 320, <https://doi:10.1080/14786451.2021.1890737>.

Table 2: Continued.

Runs #	Factor A Oil: Alcohol Molar Ratio (Mol)	Factor B Temperature (°C)	Factor C Catalyst Weight (wt.%)	Response Biodiesel Yield (%)
7	12	70	3	75
8	9	60	1	86
9	12	60	3	82
10	9	70	5	66
11	6	60	1	91
12	9	60	3	89
13	6	50	5	74
14	9	70	1	87
15	12	60	3	76
16	9	50	1	82
17	12	60	5	61



Figure 1: Synthesis and phase separation of macadamia nut biodiesel with reagent preparation and mixing (1–4), followed by phase separation of the reaction mixture (5–8).

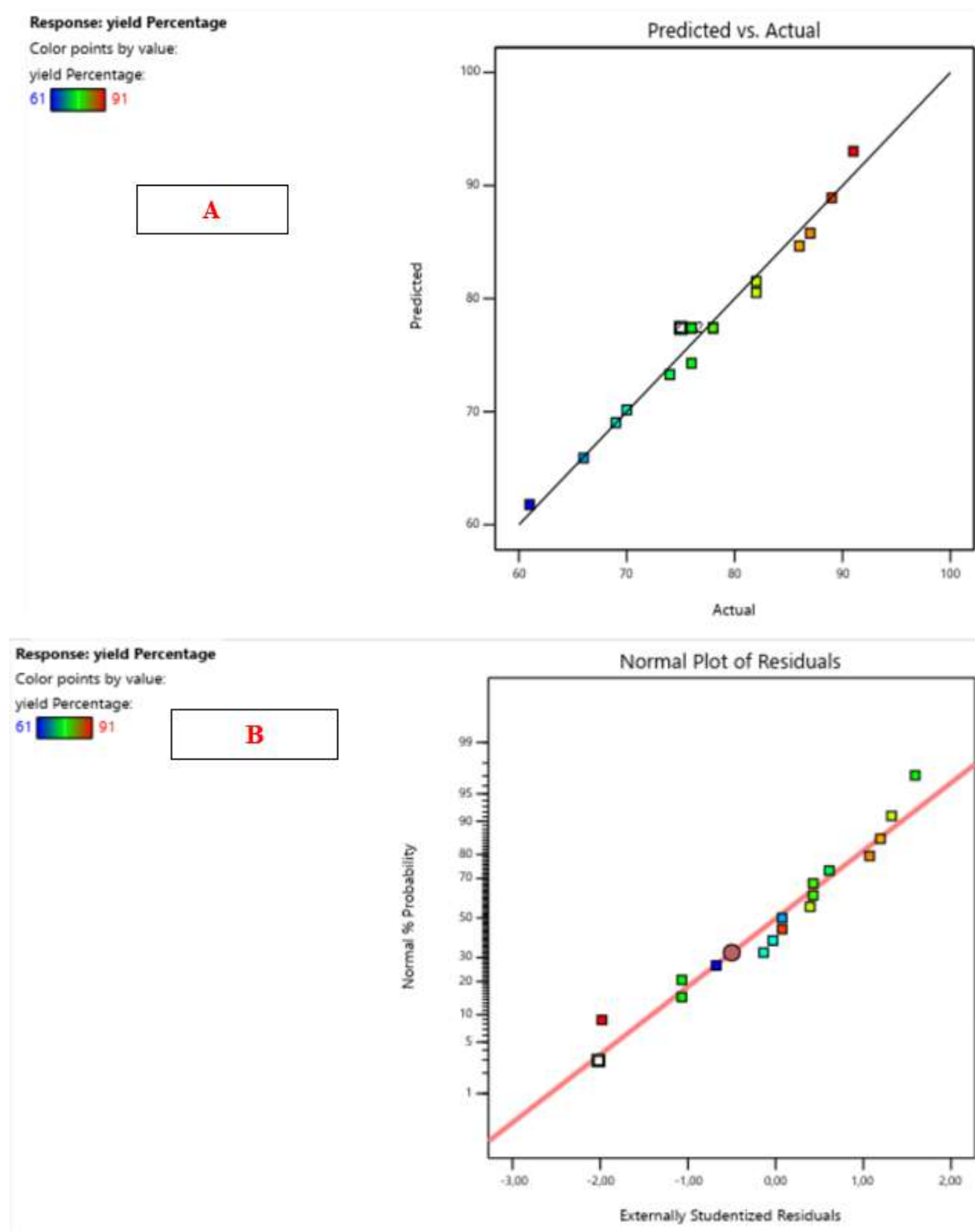


Figure 2: (A) The Predicted and Actual True Values (B) Normal Plot of Residuals (KOH).

Physicochemical analysis revealed that the biodiesel produced from MNO had properties comparable to both petroleum diesel and ASTM D6751 specifications. The viscosity of 4.07 mm²/s falls comfortably within the ASTM range of 1.9–6.0 mm²/s, ensuring proper fuel atomization in diesel injectors. The flash point of 143.7 °C is higher than that of conventional diesel, making the biodiesel safer to handle and transport. The cetane number of 52 is slightly above the ASTM minimum of 45, suggesting excellent

ignition quality and smoother engine operation⁹. The detailed values are listed in Table 3 and Table 4, which also highlight that the density, cloud point, and pour point of macadamia biodiesel align with acceptable ranges. These findings position macadamia biodiesel as a high-quality renewable fuel.

Table 3: Physicochemical properties.

Parameters	Values
Density at 15°C kg/m ³	869.2
Pour point (°C)	0
Acid value (mg KOH/g)	0.49
Cloud point (°C)	8
Viscosity (mm ² /sec) @ 40°C	4.07
High heating value (KJ/Kg)	40.24
pH	7,2
Specific gravity	0.878
Fire point (°C)	120.30
Flashpoint (°C)	143.70
Cetane number	52

Table 4: Physicochemical properties vs ASTM standards continued.

Parameters	Produced biodiesel	ASTM D6751	Diesel (ASTM D975)
Density	869.2	-	832
Acid value (mg KOH/g)	0.49	0.80 (max)	-
Flash point (°C)	143.70	100-170	60 to 80
Viscosity (mm ² /sec) @ 40°C	4.07	1.90 to 6.0	1.3-4.1
High heating value (KJ/Kg)	40.24	-	42
Cloud point	8	-3 to 12	-15 to 5
pH	8.7	7 to 9	-
Specific gravity	0.878	0.87 to 0.98	0.85
Fire point (°C)	120.30	-	-
Cetane number	49.97	> 45	40 – 50
Pour point (°C)	0	-15 to 13	(-35) -15

Spectroscopic analysis provided further confirmation of biodiesel formation. The GC-MS chromatogram (Figure 3) identified key fatty acid methyl esters (FAMES), notably oleic acid methyl ester as the dominant component, followed by palmitic and lauric acid methyl esters. Oleic acid contributes to fuel stability and higher cetane number, while palmitic acid enhances oxidative stability. The FTIR spectrum (Figure 4) displayed characteristic ester absorption bands, particularly strong C=O stretching around 1740 cm⁻¹ and C–O stretching near 1170 cm⁻¹, which are clear indicators of

⁹G. Knothe, “Designer biodiesel: optimizing fatty ester composition to improve fuel properties,” *Energy Fuels*, 22 (2008): 1358–1364, <https://doi.org/10.1021/ef700639e>.

transesterification¹⁰. Together, these results confirm successful conversion of macadamia oil into biodiesel.

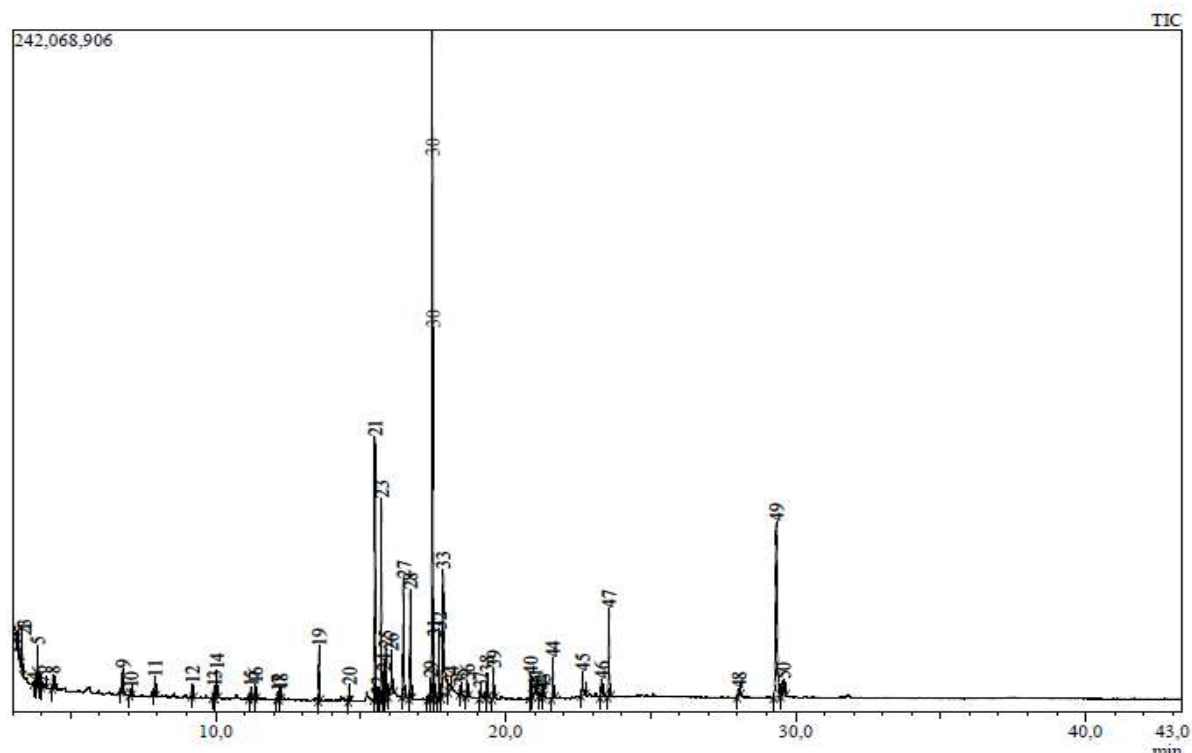


Figure 3: The GC-MS Chromatogram of KOH Biodiesel.

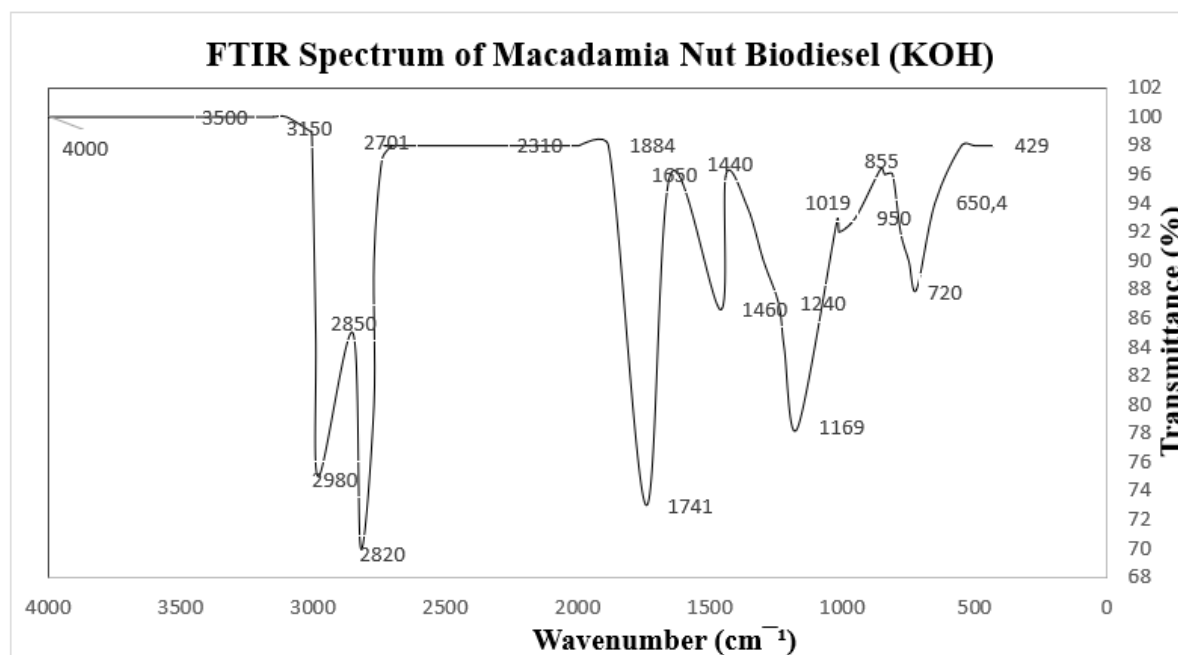


Figure 4: FTIR spectrum.

Beyond laboratory validation, these results carry broader implications. The favourable properties of macadamia biodiesel suggest potential for blending with petroleum diesel at ratios of 10–20% (B10–B20), commonly used in commercial biodiesel markets. Furthermore, South Africa's significant

¹⁰Dubé et al., “A Comparison of Attenuated Total Reflectance-FTIR Spectroscopy,” 600, <https://doi.org/10.1007/s11746-006-0948-x>.

macadamia production provides a sustainable, locally available feedstock that could support rural economic development while reducing dependence on imported fossil fuels¹¹.

Conclusion

This study established macadamia nut oil as a viable and high-performing feedstock for biodiesel production. Using KOH catalyst, optimal transesterification conditions yielded up to 91% biodiesel. The produced biodiesel met ASTM D6751 specifications and exhibited fuel properties comparable, and in some cases superior, to conventional diesel. These findings support the potential of macadamia biodiesel as a sustainable alternative fuel, particularly in regions where macadamia cultivation is abundant.

In addition to confirming its technical viability, the study highlights the strategic role macadamia biodiesel could play in South Africa's renewable energy mix. With increasing global emphasis on decarbonization, scaling up biodiesel production from non-food feedstocks like macadamia oil could diversify the energy portfolio while generating socio-economic benefits for rural communities. Future work should explore heterogeneous catalysts for improved recyclability, continuous transesterification processes for industrial application, and performance testing of macadamia biodiesel in diesel engines under real operating conditions.

Acknowledgements

The authors would like to thank the African Rainbow Minerals for the full study and experimental sponsorship and support. Gratitude is extended to University of Johannesburg, Department of Chemistry and Chemical Engineering for facilities.

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¹¹W. N. M. Wan Ghazali, et al., "Effects of Biodiesel from Different Feedstocks on Engine Performance and Emissions: A Review," **Renewable and Sustainable Energy Reviews**, 51 (2015): 585–602, Accessed 15 September 2024, <https://doi.org/10.1016/j.rser.2015.06.031>

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Chapter 31

SEAWEED FOAM: A Bio-foam Material for a New Type of Home-compostable Packaging Products

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Abstract

The global burden of synthetic packaging waste persists because durable plastics are used for disposable products. Emerging decomposable foams made from cornstarch raise ethical concerns by diverting food resources while hunger remains. SEAWEED FOAM presents an alternative: a fully organic, home-compostable material derived from seaweed that requires no arable land and is suitable for packaging. This approach supports the European Green Deal by reducing pollution and improving resource efficiency.

Using design-oriented research methods, the project engineered a homogeneous bio-foam by processing seaweed waste. The material's suitability for diverse packaging uses was assessed with emphasis on performance under environmental stressors such as moisture and sunlight. Prototypes were fabricated, rigorously tested in these conditions, and exhibited at international design shows, where user feedback informed iterative refinements.

Results indicate that SEAWEED FOAM enables home-compostable secondary packaging—cushioning, packing peanuts, and protective padding—for consumer products like backpacks and helmets. Free of harmful additives, the material is non-toxic, safe, and even edible. It maintains structural integrity under adverse conditions and offers strong impact resistance and cushioning that meet disposable packaging requirements, protecting goods during transport and storage. After use, it can be home-composted or used as fertiliser, returning harmlessly to natural systems. Overall, the research demonstrates the practicality and environmental value of SEAWEED FOAM as a significant advance in sustainable bio-foam packaging.

Keywords: *Seaweed Foam; Compostable Packaging; Packaging Design; Renewable Resources; Circular Design*

Introduction

Single-use packaging often outlives the task it performs. From a design viewpoint, the brief is to align material lifetimes with use lifetimes while preserving protection, tactility and brand experience. Starch foams indicate a route away from petro-plastics but remain tied to edible crops, an uneasy fit for circular design.

Seaweed sets a different brief: it grows in the ocean without irrigation or fertilisers and does not compete with arable land. SEAWEED FOAM explores a material system made only from seaweed and water¹. A

¹Food and Agriculture Organization of the United Nations (FAO), "Seaweeds Used as a Source of Agar," accessed 8 September 2025, <https://www.fao.org/4/y4765e/y4765e05.htm>

pourable paste is cast in design-led moulds and air-dried into lightweight, cushioning parts with a natural surface feel. The intention is twofold: (1) material adequacy for secondary packaging in short delivery journeys and everyday handling; (2) clear communication of a benign end-of-life that reduces “eco-guilt” at disposal. This direction aligns with EU policy objectives under the Packaging and Packaging Waste Regulation (PPWR)².

Problem Framing

For protective packaging, fitness-for-use sits at the intersection of:

- Tactility and sound (how it feels/sounds when handled, opened and discarded)
- Functional assurance (cushioning, scuff resistance, shape retention through delivery)
- End-of-life clarity (disposal that is intuitive, local and guilt-free)

Conventional foams score highly on assurance but poorly on end-of-life. Biodegradable starch foams improve end-of-life yet entangle packaging with food systems. Using non-food marine biomass, SEAWEED FOAM addresses this mismatch while retaining familiar, reassuring handling cues.

Materials and Methods

Seaweed Species and Sourcing

The bio-foam is formulated from seaweeds available in the Baltic region—primarily red algae (e.g., *Furcellaria lumbricalis*)³ and brown algae of the genus *Fucus* (Figure 1).



Figure 1: Baltic seaweed feedstock. Brown macroalgae (*Fucus spp.*) are used alongside regional red species (*Furcellaria lumbricalis*) in current sourcing.

²European Commission, “Packaging and Packaging Waste Regulation (PPWR) — overview,” accessed 2 September 2025, https://environment.ec.europa.eu/topics/waste-and-recycling/packaging-waste/packaging-waste-regulation_en

³M. Saluri et al., “Structural Variability and Rheological Properties of Furcellaran,” *Food Hydrocolloids* 113 (2021)

To ensure consistency and scalability, collaboration is in place with Estonian suppliers of furcellaran (a naturally gelling seaweed extract) and Norwegian alginate suppliers⁴. Where appropriate, well-characterised by-products (e.g., fine fibres) are incorporated. This keeps sourcing regional and non-food, avoids ad-hoc beach-cast dependence, and leverages existing industrial quality control (local collections, if used, follow permits and specification checks).

Formulation and Processing

A straightforward studio-to-pilot workflow is used. A seaweed-based mix is hydrated and blended to a pourable paste, then cast into silicone or rigid moulds (S/M/L/XL) or spread as sheets for inserts.

Parts are air-dried at ambient or with gentle airflow and demoulded (Figure 2); off cuts are returned to the wet mix to minimise waste. Air-drying also produces a fibrous, lightweight cell microtexture that contributes to the material's natural tactility (Figure 3).



Figure 2: Cast rectangular pad: Air-dried pad for lining/spacing; dimensions are set by the mould family.



Figure 3: Surface microtexture: Fibrous, lightweight cell structure from air-drying gives a natural tactility.

⁴R. Abka-khajouei et al., "Structures, Properties and Applications of Alginates," *Polymers* 14, no. 12 (2022), <https://doi.org/10.3390/polym14122452>

Form-giving is prioritised over additives: dimensions are selected via the cavity rather than by changing the recipe. For air-dried parts single-wall sections are kept to about 2 cm to support even drying and shape stability; thicker pieces can be built up by laminating thinner layers. The mould library acts as a design system, enabling families of parts without proliferating formulations.

Design Methods

A combination of research-through-design (RtD), material-driven design (MDD) and the Double Diamond structured the work:

- Discover — desk research, material probes (swatches at varying thickness/density) and bodystorming of packing/unboxing rituals to surface tacit needs (e.g., low dusting on dark garments; clean handling).
- Define — a brief matrix balancing cushioning targets, humidity tolerance, sensory expectations and on-pack communication; definition of two archetypes (pads/blocks, loose-fill) and a family of moulds.
- Develop — iterative prototype loops (sketch → mould → air-dry → handle → adjust), guided by a simple scoring sheet covering feel, edge integrity, dusting, odour neutrality, squeeze recovery, shape retention after brief moisture contact, and disposal clarity.
- Deliver — public showings and co-evaluation with designers, brands and logistics partners; refinement of plain-language disposal messaging and use-scenarios (e.g., cosmetics, small electronics, refills).

Performance Evaluation

Prototypes were evaluated in the ways people handle packaging: grip, stack, squeeze and short drops for small parcels; brief exposure to daylight and steamy rooms; and home-compost checks for end-of-life. To broaden stakeholder input, prototypes were presented at Prototypes for Humanity during COP28 (Dubai, 28–30 Nov 2023), MaterialDistrict Utrecht (8–10 Mar 2023; 6–8 Mar 2024), and the EU Strategy for the Baltic Sea Region Annual Forum 2023 (Riga, 4–5 Oct 2023). Feedback from designers, architects, brand owners and policymakers informed refinements to density, surface finish and geometry.

Industry Engagement

Since 2023, SEAWEED FOAM has attracted inquiries and evaluation requests across consumer goods, mobility, packaging, hospitality and design. Interested parties include Unilever, CHANEL, Toyota, Aston Martin Lagonda Ltd, Normann Copenhagen, MAX Luxury Packaging, Semcon Sweden AB, WFN Fish Farm (Nova Scotia), Thermowave Packaging, Estrahub (thermal insulation), EDRINGTON, PENTATONIC, TVS Motor Company Ltd, Merveyl Hotel Supplies, CARRE BASSET, Luna & Solis, Sakshi Innovations and Threadz NOLA (upholstery). Additional interest came from material libraries, research projects and independent designers. These engagements focus on void-fill, bottle cushioning and pads/blocks, and inform pilot validation in fulfilment environments.

Results

SEAWEED FOAM parts retained shape and cushioning behaviour after short-term humidity/light exposure, typical of last-mile logistics. Hands-on trials also demonstrated the material's suitability for loose-fill applications, where it surrounds products and fills voids in a standard e-commerce box (Figure 4). In home-compost settings, samples fragmented and disintegrated within a short horizon (target ≤ 180 days)⁵ without visible residues. The recipe is benign and simple (seaweed + water). User feedback highlighted pleasant tactile warmth, low dusting, and clear disposal messaging.



Figure 4: Loose-fill “packing peanuts” in use. Seaweed foam surrounds products and fills voids in a standard e-commerce box.

Industrial Scalability and Input Volumes

At pilot scale two archetypes were produced: (i) rectangular pads/blocks in multiple sizes for lining and spacing, and (ii) loose-fill “packing peanuts.” Pads slide straight into everyday packing workflows, while peanuts behave like conventional loose-fill. Dimensions are standardised via a shared mould set that maps to parcel formats. Off-cuts, where present, are returned to the wet mix. Co-location with packaging partners or seaweed processors shortens logistics and supports small, local runs as demand grows. Pilot deployments with partners will validate handling and cushioning in fulfilment, followed by third-party home-compostability and safety certification.

Environmental and Safety Considerations

The bill of materials is seaweed + water, free from harmful additives. After use, parts are home-compostable and may serve as a benign soil amendment. Production avoids petrochemical monomers and arable land, supporting circularity goals. Future work includes a full life-cycle assessment (LCA) and certification under recognised home-compost schemes, alongside transparent on-pack guidance

⁵ÜV AUSTRIA, “OK compost HOME — Certification Scheme,” accessed 2 September 2025, <https://en-trustit.tuv.at/ok-compost-home-en/>

for disposal or simple re-use. Figure 5 symbolically evokes the material's marine origin and a benign end-of-life narrative, suggesting reintegration into natural systems rather than persistence as pollution.



Figure 5: End-of-life narrative (symbolic): Visualising a benign material story; this is not a disposal pathway—home compost is the intended end-of-life.

Discussion and Limitations

SEAWEED FOAM is a material-system guided by non-food circularity, home-compostable by design, and credible tactility. In this study, performance comes from cast form and sizing rather than additives, with two practical archetypes: pads/blocks for lining/spacing and loose-fill for void-fill (dimensional constraints and lamination options in Section 2.2). During demonstrations, plain-language disposal guidance (“home-compost or place with organic waste where permitted”) and a simple bill of materials (seaweed + water) helped build trust.

Performance can drift under prolonged high humidity; seasonal differences in seaweed supply require clear specs for consistency; and drying efficiency should continue to improve (better airflow, heat recovery). Standard-based lab tests (impact curves, creep, compost disintegration) are in progress. On the experience side, continued refinement of CMF (colour–material–finish) supports consistent aesthetics and odour neutrality.

Conclusion

SEAWEED FOAM reframes protective packaging as a designable, bio-based system rather than a petrochemical default. Regional species and sourcing are specified, homogeneous parts that provide effective cushioning and short-term stability are demonstrated, and validation through public demonstrations and industry engagement is documented. The contribution is threefold: (1) clear principles for non-food, home-compostable packaging; (2) form-first, casting-led strategies that deliver performance with a minimal recipe; (3) a modular, converter-ready pathway suitable for distributed capacity. Next steps include standardised testing, refined end-of-life messaging and pilot deployments

with partners—advancing a designed route to compostable protective packaging that returns safely to the biosphere after use.

Acknowledgements

This work was supported by the “Promotion of Competence Centre Activities: Vilnius Academy of Arts Entrepreneurship Programme” (Project No. 01.2.2-CPVA-K-703-04-0002, 2021), and by Cultural and Creative Industries: Cultural Startups 2023-1, “Dissemination, market entry and promotion in Lithuania and abroad of a seaweed-based biodegradable packaging material.”

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Chapter 32

Transforming Agricultural and Plant-based Byproducts into Compostable Hygiene Materials for a Circular Economy

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Abstract

This study investigates cellulose fibres from agricultural byproducts for use in absorbent materials. Harvest residues such as stalks and leaves were sourced from local farms and processed through mechanical and chemical treatments to extract cellulose fibres. The cellulose fibres were used to produce nonwovens and fluff pulp, which were evaluated through in-house and external absorbency testing. Fluff pulp showed performance significantly greater than kraft wood pulp, while wet-laid nonwovens absorbed 9.5 mL/g of simulated menstrual fluid. Pilot-scale composting tests (ISO 16929:2021) demonstrated that a prototype menstrual pad (A-Pad) made from agricultural byproducts achieved $96.7\% \pm 3.3\%$ disintegration after 63 days, outperforming bamboo ($31.8\% \pm 7.6\%$) and cotton-based ($46.4\% \pm 12.2\%$) pads. Converting agricultural residues into compostable materials provides a sustainable alternative to cotton, bamboo, wood pulp, and synthetics, reducing landfill waste and supporting rural economies, while advancing circular practices in the hygiene industry.

Keywords: *Cellulose fibres, Agricultural and plant-based byproducts, Compostable materials, Absorbent hygiene products, Circular economy*

Introduction

The absorbent hygiene industry faces growing demand for sustainable materials to mitigate the environmental impact of non-degradable waste. Conventional products such as menstrual pads and diapers rely on plastics (polypropylene, polyethylene) and superabsorbent polymers, which can take up to 800 years to degrade in landfills¹. Alternatives marketed as sustainable often use cotton, bamboo, or wood-based fluff pulp, which, though compostable under specific conditions, are resource-intensive. Cotton requires ~10,000 L of water per kg and accounts for 16% of global insecticide use on only 2.3% of arable land². Bamboo textile processing requires toxic chemicals (e.g., carbon disulfide), increasing its environmental footprint³. Wood pulp production drives deforestation and high energy use⁴.

¹Smitikana Ray et al., “Sanitary Waste and Microplastic Pollution in the Euro-Mediterranean Region: Challenges and Solutions,” *Euro-Mediterranean Journal for Environmental Integration* (published July 16, 2025), <https://doi.org/10.1007/s41207-025-00879-y>.

²Zhang Zhenggui et al., “Environmental Impacts of Cotton and Opportunities for Improvement,” *Nature Reviews Earth & Environment*, 4 (2023): 703–715, <https://doi.org/10.1038/s43017-023-00476-z>.

³Amjad, Akhtarul Islam, “Bamboo Fibre: A Sustainable Solution for Textile Manufacturing,” *Advances in Bamboo Science* 7, (2024) (May): 100088, <https://doi.org/10.1016/j.bamboo.2024.100088>.

⁴Zhao, Qingjian et al., “Energy Flows and Carbon Footprint in the Forestry-Pulp and Paper Industry,” *Forests* 10 no. 9 (2019): 725, <https://doi.org/10.3390/f10090725>.

Burning agricultural residues produces ~3.5% of global greenhouse gas emissions⁵, releasing significant amounts of CO₂, CH₄, and N₂O into the atmosphere, contributing to climate change, with significant portions burned in fields in countries India⁶ and the USA⁶ exacerbating air pollution and greenhouse gas emissions. This study introduces a circular economy approach, transforming agricultural byproducts such as banana, hemp, and bullrush into compostable absorbent materials for hygiene products. Valorising agricultural waste minimizes landfill use, reduces resource depletion, and supports rural economies, while advancing scalable, high-performance alternatives to conventional materials.

Results and Discussion

Cellulose Fibre Extraction

Agricultural residues were mechanically processed to break down stalks and increase surface area. A subsequent chemical treatment extracted cellulose fibrils from the surrounding hemicelluloses, lignin, and waxes⁷. The material was impregnated with reagents, strained, washed, and dried, yielding 40–60% after combined mechanical and chemical losses.

Fibre Characterisation

After extraction, cellulose fibre yield varied with the type and quality of agricultural material. The fibres differed in length, bulk density, and absorbency, and could be processed into nonwovens for use in disposable hygiene products such as menstrual pads, incontinence pads, maternity pads, and diapers.

Fluff pulp, a highly absorbent material typically made from softwood kraft, was reproduced from agricultural fibres by defibrillation in a blender, producing a soft, absorbent⁸.

Nonwovens were produced using a wet-laid method. Extracted fibres were dispersed in water, filtered through a fine screen to form a mat, and then dried in an oven and at room temperature.

Test samples (250 g/m², 9 × 9 cm) absorbed about 9.5 times their mass in simulated menstrual fluid, as shown in Table 1. Specifically, a nonwoven with a basis weight of 250 g/m² absorbed 2374 g of fluid per m², equivalent to 2381 mL/m² (given the fluid density of 0.997 g/mL). This performance exceeds cotton-based absorbents (6–8 g/g) and matches the upper range of commercial wood pulp fluff (8–11 g/g), showing that nonwovens from agricultural byproducts can compete with conventional absorbent materials.

⁵Ritchie, Hannah, “GHG Emissions by Sector,” *Our World in Data*, Accessed August, 2025, <https://ourworldindata.org/ghg-emissions-by-sector>.

⁶Lan, Ruoyu et al., “Air Quality Impacts of Crop Residue Burning in India and Mitigation Alternatives,” *Nature Communications* 13 (2022): 6537, <https://doi.org/10.1038/s41467-022-34093-z>.

⁷Parida, Pramod Kumar et al., “Extraction of Natural Cellulosic Fiber from *Myriostachya wightiana* Stems Using Chemical Retting and Its Characterization for Bio-Composite Applications,” *Cellulose* 30 (2023): 8819–8837, <https://doi.org/10.1007/s10570-023-05438-8>.

⁸Ismaeilimoghadam, Saeed et al., “Manufacturing of Fluff Pulp Using Different Pulp Sources and Bentonite on an Industrial Scale for Absorbent Hygienic Products,” *Molecules* 27 no. 15 (2022): 5022 <https://doi.org/10.3390/molecules27155022>.

Table 1: Absorbency test results of nonwovens made from 100% cellulose fibres.

Sample	Dry Mass (g)	Wet Mass (g)	Absorbed Fluid (g)	Absorbency ($g_{\text{fluid}}/g_{\text{textile}}$)
1	0.913	9.817	8.904	9.752
2	0.682	7.158	6.476	9.496
3	0.735	7.527	6.792	9.241
Average	–	–	–	9.496

Absorbency Testing of Fluff Pulp

To evaluate fluff pulp absorbency, cylindrical test pieces (3 g, 50 mm diameter) were prepared using a dust cyclone and vacuum to evenly distribute pulp into a 3D-printed mold, as shown in Figure 1. Each piece was placed on a perforated disk above 900 mL of water, loaded with 500 g for uniform pressure, immersed for 2 min, then drained for further 2 min. Absorbent capacity was calculated as $(W_{\text{wet}} - W_{\text{dry}}) / W_{\text{dry}}$, where W_{wet} and W_{dry} are the wet and dry weights of the test piece, respectively. This in-house method provided reproducible results with simple equipment.

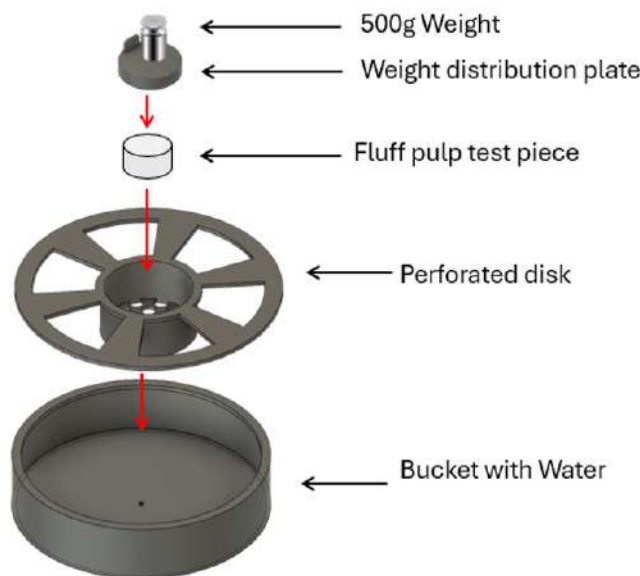

Figure 1: 3D-printed test piece for absorbency testing.

Table 2 compares the absorbency of kraft softwood pulp (control) with fluff pulp from bullrush, banana, and hemp.

Table 2: Average absorbency test results of fluff pulp from bullrush leaf, banana stem, and hemp hurd. Three replicates of each sample type were tested.

	Dry Mass (g)	Wet Mass (g)	Absorbency ($g_{\text{fluid}}/g_{\text{textile}}$)
Wood pulp (Control)	2.99	33.32	10.16
Bullrush fluff pulp	2.97	48.62	15.37
Banana fluff pulp	2.94	48.31	15.43
Hemp fluff pulp	3.02	55.13	17.25

Disintegration Under Compost Conditions

Composting is the aerobic biodegradation of organic waste into nutrient-rich material⁹. Assessing disintegration at pilot scale is essential, since the compostability of raw cellulose fibres may differ once processed into products. To test this, a prototype pad (A-Pad) made from our cellulose fibres was compared with two commercial products: a bamboo-based pad (B-Pad) and a cotton-based pad (C-Pad), as disclosed on their respective websites.

Test products used in this study:

- **A-Pad:** Composed of a pressed banana fibre layer, a hemp fibre absorbent core, hemp lining, a starch-based plastic wrapper, and a plant-based adhesive.
- **B-Pad:** Composed of a compostable wrapper, a bamboo/cornstarch fibre absorbent layer, a food-grade non-toxic adhesive, and a bioplastic pad lining.
- **C-Pad:** Composed of a bioplastic wrapper, an organic cotton/sustainable wood pulp absorbent layer, and a bioplastic pad lining.

Disintegration followed ISO 16929:2021¹⁰. The degree of disintegration for each test product was calculated using the equation: $(\frac{mass_{final} - mass_{initial}}{mass_{initial}} \times 100)$.

Three compost tumblers were used: one control and two test replicates (Trial A, Trial B), each containing 12 pads (four of each type). Pads were sealed in nylon mesh bags with biowaste (food scraps, yard waste, and unbleached paper) and inoculated with mature compost. Tumblers were turned weekly, with biowaste replenished to sustain volume and temperature. Compost temperature, pH, moisture, and odour were monitored regularly to maintain optimal conditions, with weekly turning for aeration and mixing.

After 63 days, temperature (max 55–57C, avg. 43C), moisture, and pH stayed within optimal ranges. Consistently earthy odours confirmed stable aerobic composting.

The following Table 3 shows a summary of the results from the disintegration testing:

Table 3: Average test product characteristics at the end of the 9-week compost disintegration experiment. Standard deviations are shown in parentheses.

	Average of Initial Mass (g)	Average of Final Dry Mass (g)	Average of Degree Disintegration
A-Pad	14.02(3.73)	4.60(3.13)	96.7%(3.3%)
B-Pad	7.32(0.06)	4.98(0.53)	31.8%(7.6%)
C-Pad	7.69(0.05)	4.12(0.96)	46.4%(12.2%)

⁹Genetu, Amare, “Composting Technology for Municipal Solid Waste Management and Production of Organic Fertilizer,” *Advances in Environmental Waste Management & Recycling* 7 no. 2 (2024): 1–13.

¹⁰International Organization for Standardization (ISO), *ISO 16929:2021 Plastics—Determination of the Degree of Disintegration of Plastic Materials under Defined Composting Conditions in a Pilot-Scale Test*, 4th ed. (Geneva: International Organization for Standardization, 2021).

Conclusion

This study demonstrates that agricultural byproducts such as banana stalks, hemp hurds, and bullrush biomass can be transformed into high-performance, compostable absorbent materials for hygiene products. Our fibres outperformed conventional, resource-intensive cotton and bamboo in both absorbency and compostability, with prototype pads achieving nearly complete disintegration under ISO 16929 conditions.

Extracted cellulose fibres were processed into fluff pulp and nonwovens, with fluff pulp absorbency reaching 15.37 g/g (bullrush), 15.33 g/g (banana), and 17.25 g/g (hemp), values much higher than the 10.16 g/g of standard wood pulp. Pilot-scale composting (ISO 16929:2021) showed that a prototype A-Pad, made from banana and hemp fibres, disintegrated by $96.7\% \pm 3.3\%$ after 63 days, outperforming bamboo-based ($31.8\% \pm 7.6\%$) and cotton-based ($46.4\% \pm 12.2\%$) commercial pads, underscoring the materials' disintegration under composting conditions.

While further testing and industrial scale-up are needed, the results show that agricultural residues can rival and surpass established raw materials. By turning overlooked waste streams into valuable fibres, this work reduces landfill pressure, conserves resources, and supports rural economies.

The findings point toward a circular future for the hygiene industry, one where performance and sustainability go hand in hand, and where agricultural byproducts become a cornerstone of low-impact, next-generation materials.

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Chapter 33

AI-optimized Green Hydrogen Production from Biomass and Wastewater, and Integrated CO₂ Capture Pathways via Solar-Fenton and Natural Catalysts

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Abstract

This study introduces an integrated, scalable approach for sustainable hydrogen generation that combines artificial intelligence optimization, wastewater valorization, and carbon capture into a unified platform. The core process involves an AI-driven heterogeneous Solar-Fenton system utilizing mesquite biomass and fish waste to produce natural catalysts for the treatment of petroleum refinery effluent (PRE). The treated water is reused in hydrogen electrolysis, reducing freshwater dependency and enabling hydrogen production in arid regions such as Oman.

The Solar-Fenton process achieved up to 95% pollutant removal, producing 45–50 kg of hydrogen per 1000 m³ of treated wastewater at 99.998% purity. The integration of Genetic Algorithms (GA) and Artificial Neural Networks (ANN, R² = 0.95) optimized process variables, lowering electrolysis energy consumption by nearly 30% and reducing hydrogen production costs by 40–50% relative to conventional grey or blue hydrogen methods. Additional innovations, such as a compact solar-driven hydrogen fuel cell and a sodium-metal NASICON electrochemical cell capable of simultaneous CO₂ capture and hydrogen generation, extend the concept to a circular, multi-pathway hydrogen ecosystem. Collectively, these technologies achieve an 85% reduction in CO₂ emissions, save 50% of freshwater use, and provide net positive economic value through carbon credits and bicarbonate production. The project is in line with Oman Vision 2040 and the United Nations Sustainable Development Goals (SDGs 6, 7, 9, 12, and 13), offering a model for sustainable hydrogen economies elsewhere in the world.

Keywords: *Solar-Fenton, Wastewater valorizations, Artificial intelligence optimization, Proton exchange membrane electrolysis, NASICON membrane, CO₂ capture*

Introduction

Petroleum refinery effluent (PRE) is one of the most formidable industrial wastes due to its toxicity, recalcitrance, and resistance towards traditional treatment alternatives. With phenols, hydrocarbons, and heavy metals, PRE is highly hazardous to the ecosystem and public health. The sustainable development of effluent management thus emerges as a worldwide environmental need. In the Sultanate of Oman, lacking economic diversification and a shift towards renewable blending in the

national agenda under Oman's Vision 2040, PR management is a platform to transform waste into a clean energy source¹.

This article reports on a holistic approach to green H₂ production by using a heterogeneous solar-Fenton process assisted with AI optimization. It converts wastewater into a usable feedstock for hydrogen synthesis by incorporating two further technologies, compact solar-powered hydrogen fuel cells, and an electrochemical system based on sodium-metal NASICON to capture CO₂, resulting in a circular economy of H₂. All these pathways provide an infrastructure for countries interested in integrating good practices of environmental protection with the transition towards renewable energy².

Experimental Setup

A prototype Solar-Fenton tester was developed to simulate actual operating conditions in places that are abundant in solar radiation. It consisted of a central mixing tank provided with mechanical agitation, circulation pumps for homogenization of catalysts, and a hybrid UV-solar irradiation system to trigger the generation of hydroxyl radicals. Pre-treatment of oil refinery effluent. The initial pre-treatment of the petroleum refinery was carried out by vacuum filtration to separate suspended solids and oil residuals, followed by adjusting pH with diluted sulfuric acid at its optimum Fenton reaction conditions.



Figure 1: Experimental setup prototype showing the circulation system, mixing tank, and UV/solar integration.

This configuration allowed controlling joint reaction parameters with enough industrial scalability. The treated effluent showed a significant reduction in turbidity and color intensity, which indicates that organic degradation had taken place before electrolysis.

Catalyst Synthesis and Characterisation

The heterogeneous catalyst used in the Solar-Fenton process was hematite ($\alpha\text{-Fe}_2\text{O}_3$), synthesized through an eco-friendly combustion technique using iron nitrate precursors and locally sourced organic fuels.

¹Chong et al., "Recent Developments in Photocatalytic Water Treatment Technology: A Review," *Water Research*, 44, no. 10 (2010): 2997–3027 <https://doi.org/10.1016/j.watres.2010.02.039>.

²Goodenough, J. B., and H. Y.-P. Hong, "Sodium Ion Conduction in NASICON," *Materials Research Bulletin*, 11, no. 2 (1976): 203–220 [https://doi.org/10.1016/0025-5408\(76\)90077-5](https://doi.org/10.1016/0025-5408(76)90077-5).

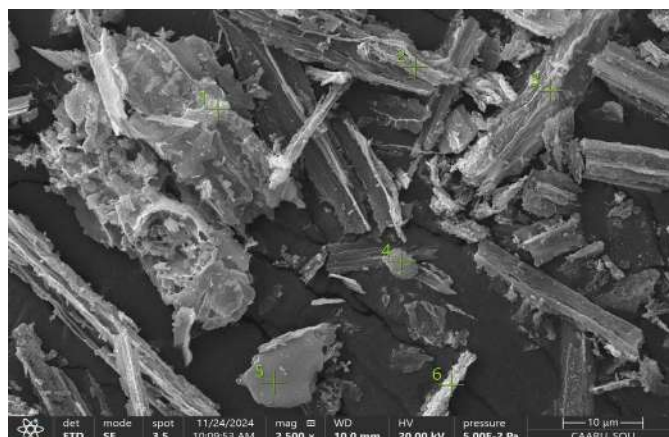


Figure 2: SEM micrograph of hematite catalyst.

Spherical and well-distributed particles with high surface area required for catalysis were observed using scanning electron microscopy³. Energy-dispersive X-ray (EDS) study revealed iron and oxygen as the major elements, suggesting that higher purity/stability is present. Fourier transform infrared spectroscopy showed bands related to Fe–O stretching at around 470 cm^{-1} and Fe–O–Fe bending between 540 cm^{-1} , and X-Ray diffraction patterns displayed well-developed peaks associated with the rhombohedral crystal phase of hematite, with an estimated crystallite size $\sim 20\text{ nm}$. These displays of physicochemical properties could facilitate solar light-induced radical species generation, long catalyst life, and low contamination, which are prominent parameters in subsequent hydrogen production.

Optimization of Reaction Conditions

The optimization was carried out based on a combination of response surface methodology (RSM) and genetic algorithms (GA) to facilitate the systematic consideration of main variables, namely, pH, catalyst dose, reaction time, and oxidant concentration. The results showed that pH was the most important variable with respect to TOC and COD removal. The optimum pH was found to be between 4.5 and 5.0, in line with the highest activity of hydroxyl radical generation in Fenton systems.

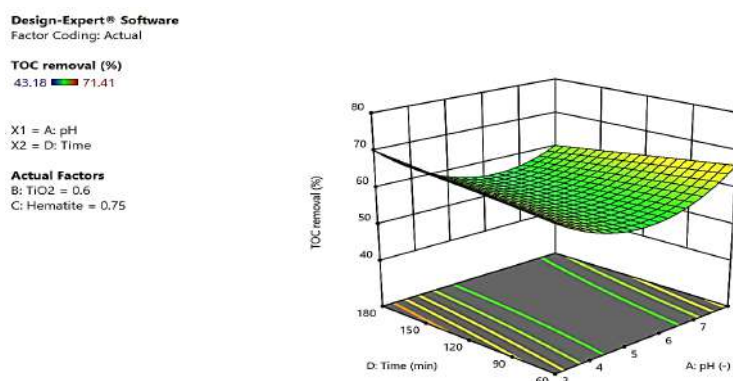


Figure 3: 3D surface plot showing pH vs. time vs. TOC removal %.

³International Renewable Energy Agency (IRENA), Green Hydrogen: A Guide to Policy Making, Abu Dhabi: IRENA, 2020.

Under the best conditions, the TOC and COD removal rates were 89.7% and 92.1%, markedly higher than those achieved by conventional coagulation methods (< 60%). Predictability of the process was enhanced with ANN model with an R^2 value of 0.95, which led to real-time control and adaptive energy management⁴ [4]. The AI-optimized approach therefore provided a strong platform for high purification efficiency at low cost of operation.

Integration with Green Hydrogen Production

The treated effluent obtained from the optimized Solar-Fenton process exhibited TOC values below 5 mg/L, COD below 20 mg/L, and heavy metal removal above 90%. The pH stabilized between 5.5 and 6.0, within the acceptable range for proton exchange membrane (PEM) electrolyzers. Electrolysis of this purified water produced 45–50 kg of hydrogen per 1000 cubic meters of wastewater, achieving 99.998% purity in accordance with ISO 14687 fuel cell standards.

This two-in-one process not only detoxifies industrial wastewater but also generates clean hydrogen fuel, for a water-energy nexus featured by being self-sustained and scaled-up for the treatment of industrial effluent in arid/semi-arid areas.

AI-enhanced Energy Efficiency

The incorporation of AI-based algorithms considerably improved energy efficiency at the process level for hydrogen production. The GA-ANN combined system reduced electricity consumption in an electrolysis by 30% with simultaneous maximization of catalyst and oxidant utilizations. The adaptive control features of the ANN model permitted reaction variables to be varied in an online fashion, resulting in an increase in experimental reproducibility along with continuation of steady operation. Consequently, the total hydrogen production cost decreased by 40–50% relative to grey hydrogen routes, establishing the economic competitiveness of AI-optimized wastewater-to-hydrogen technologies⁵ [5].

Supplementary Hydrogen Pathways

To complement the Solar-Fenton process, two additional systems were investigated to demonstrate a broader hydrogen ecosystem. The first was a compact, solar-driven hydrogen fuel cell designed for universities and research centers. The system operates as a closed loop, converting solar energy into electricity for water electrolysis, generating hydrogen and oxygen, and then reconverts hydrogen into electricity through a PEM fuel cell.

Although small in scale, this design functions as an educational and research platform, allowing institutions to train future engineers and scientists in hydrogen cycle technologies and contribute to national capacity building.

⁴Johnson, P., and D. Williams, "Synthetic Hematite Catalysts for Fenton Reactions." *Applied Catalysis B: Environmental*, 242, (2022): 149–159 <https://doi.org/10.1016/j.apcatb.2022.118350>.

⁵Ministry of Energy and Minerals, Oman, Oman Hydrogen Strategy – Executive Summary, 2023.



Figure 4: Closed-loop schematic of compact solar-driven hydrogen fuel cell system.

The second supplementary technology is a sodium-metal NASICON electrochemical system that unites hydrogen production with carbon dioxide capture⁶ (Goodenough and Hong 1976). At the anode, sodium oxidizes and releases sodium ions that migrate through the NASICON membrane, while at the cathode, protons from water are reduced to hydrogen gas. Simultaneously, CO₂ in the aqueous compartment reacts with sodium ions to form sodium bicarbonate⁷ [6].

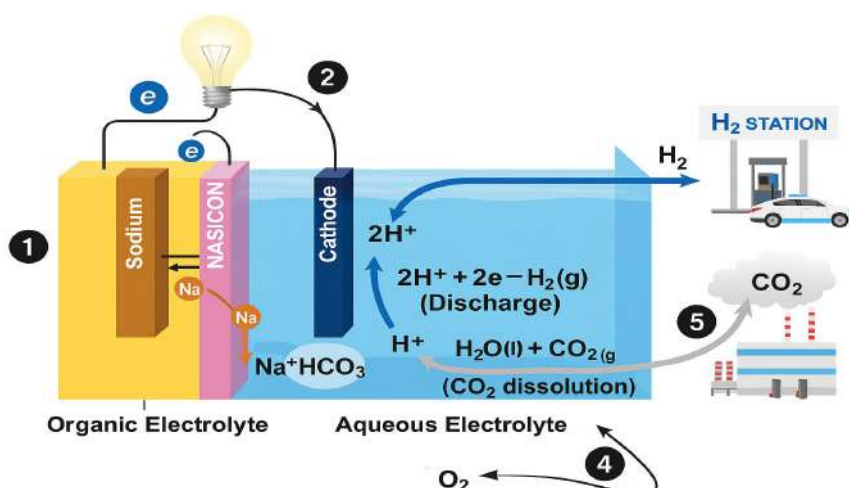


Figure 5: Schematic of the sodium NASICON system integrating hydrogen generation and CO₂ capture.

This two-fold process is aligned with two worldwide objectives: reducing carbon dioxide and producing clean energy. From an economic point of view, the use of sodium (between US\$ 3 and 5/kg) is a big advantage over lithium (US\$ 60 - 80/kg). In addition, the system yields high-purity hydrogen at US\$ 4–6 per kg and bicarbonates worth US\$ 200–400 per ton, as well as additional revenue from selling carbon credits at approximately US\$ 30–60 per ton of CO₂. The economic and environmental advantages of both these pathways also make the NASICON pathway viable from both classical as well as modern perspectives⁸ [7].

⁶Goodenough and Hong, "Sodium Ion Conduction in NASICON." *Materials Research Bulletin*, 203–220.

⁷Nidheesh, et al., "Removal of Synthetic Dyes..." *Chemical Engineering Journal*, 343 (2018): 447–471
<https://doi.org/10.1016/j.cej.2018.03.156>.

⁸Roy, R., and A. Banerjee, "Solar-Driven Photocatalysis for Degradation..." *Journal of Photochemistry and Photobiology C*, 47 (2021): 100412 <https://doi.org/10.1016/j.jphotochemrev.2021.100412>.

Environmental and Economic Impact

Huge differences were found in the integrated scheme compared with traditional hydrogen production methods. Using solar irradiation, biological catalysts, and AI-based optimization, the Solar-Fenton–electrolysis platform decreased CO₂ emissions by up to 85% relative to hydrogen blue / grey – generated from fossil resources and carbon capture⁹ [8]. Concurrently, recycled wastewater reduced freshwater use by over 50%, an essential element in the desert context. The 30% lower electrolysis energy usage and the reduced catalyst cost through utilizing waste biomass material led to energy-efficient and economically competitive hydrogen production. With the addition of the sodium NASICON process, this integrated product feature makes BMG's long-term sustainability and market potential even more compelling, given the income from bicarbonate sales and carbon credits¹⁰ [9].

Industrial Feasibility and National Relevance

Repeated operational cycles confirmed the reproducibility and stability of the Solar-Fenton process, underscoring its readiness for industrial application. The use of locally available mesquite biomass and fish waste as catalyst precursors ensures cost efficiency and sustainability. Oman's high solar irradiance, averaging more than 2200 kWh/m² / year, supports continuous operation of both the Solar-Fenton and photovoltaic-powered electrolysis systems. Pilot-scale assessments indicate that national hydrogen production could reach between 1.5 and 2 million tons annually using this integrated approach¹¹ [10].

In addition, university-scale small-sized hydrogen fuel cell system results in faster knowledge transfer and skill development, and the commercialization level of NASICON-based carbon capture platform for refineries and high-emission plants is industrially scalable. "By jointly developing these solutions, we are creating the foundation of a national hydrogen ecosystem, including education, industry, and sustainability. That they align with Oman Vision 2040 and the UN-SDGs suggests that this model has global relevance and is particularly relevant for regions aspiring to develop low-carbon and bio-resource resilient economies.

Conclusion

This analysis provides a holistic roadmap for generating green hydrogen using AI-assisted optimized wastewater treatment combined with carbon-capturing intermediations. The integrated power plant demonstrated an efficiency of pollutant removal close to 90%, a purity of local hydrogen, a reduction in energy consumption of 30% and environmental pollution by 85%. Through the combination of Solar-Fenton catalysis, AI-empowered electrolysis, and CO₂-to-bicarbonate conversion, this platform paves the way for multi-pathway sustainable hydrogen generation. Apart from its technological

⁹Tanaka, K., and M. Yamaguchi, "Recent Progress in AOPs." *Environmental Chemistry Letters*, 14, no. 2 (2016): 287–301 <https://doi.org/10.1007/s10311-016-0563-4>.

¹⁰Turner, J. A. "Sustainable Hydrogen Production," *Science*, 305, no. 5686 (2004): 972–974. <https://doi.org/10.1126/science.1103197>.

¹¹Zhou, et al., "Advances in Heterogeneous Photocatalysis." *RSC Advances* 8, no. 13 (2018): 7173–7183 <https://doi.org/10.1039/C8RA00371C>.

advancements, compact educational fuel cells allow freedom in the model for new materials and techniques; similarly, NASICON-based CO₂ capture makes this work sterling in both social and economic respects. Together, these technologies drive a circular hydrogen economy that regenerates water, captures carbon, and creates clean fuel, in line with Oman's national goals and global sustainability targets. Subsequent research will further investigate durability of catalysts, techno-economic scaling, and integration with photovoltaic power to form completely self-sustaining, emission-free hydrogen economy chains.

Acknowledgements

This research was funded by the Ministry of Higher Education, Research, and Innovation (MoHERI) under the Undergraduate Research Grant (Block Funding Program). The authors gratefully acknowledge the assistance and facilities provided by the National University of Science and Technology (NUST), College of Engineering. The authors would like to express their gratitude to Profs Ahmed Al Balushi and K. P. Ramachandran for being the mentors, Dr. Lakkimsetty Nageswara Rao, AURAK, UAE for scientific discussion, Ms. Khadija Al Balushi who helped in data acquisition, as well as Dr. Varghese who contributed to modelling and analysis. The authors are also grateful to the estates, purchase and finance Departments, and Dr. Hamood Darwish, Director of Scientific Research, their great cooperation in the pursuit of excellence.

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Chapter 34

Using Hydrokinetic Energy for Green Hydrogen and Green Oxygen Production

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Abstract

The College of the Florida Keys (CFK) and Hydrokinetic Energy Corp (HEC) developed a one-of-a-kind pilot project for sustainable fuel production with zero carbon dioxide (CO₂) emissions. The project will deploy a floating platform equipped with four patented HEC hydrokinetic turbines fortified with: (1) flow-acceleration technology, which increases energy extraction up to 300%, and (2) wildlife/debris excluders, which protect marine life and turbines, while increasing energy extraction for an additional 5-10%. Located 35 km south of Key West in the Gulfstream, this innovative project will demonstrate the most efficient extraction of energy from one of the world's most powerful oceanic currents. The turbines will produce 48 kW of continuous electrical current, powering onboard reverse osmosis (RO) desalination units and feeding freshwater into onboard electrolyser units that split water molecules (H₂O) into “green” hydrogen (H₂ atoms) and “green” oxygen (O₂ atoms). The term “green” is used because the power source splitting the molecules is a renewable energy source, as opposed to “black” or “grey” hydrogen made from burning fossil fuels. Daily production of green H₂ is calculated at 19.8 kg of H₂ and 159 kg of O₂. Gases will be shipped onshore for energy production at CFK. Green H₂ will be used to power aquaculture operations at CFK, and green O₂ will be used to sustain marine organisms cultured for education, research, and environmental restoration (e.g., coral restoration). This pioneering pilot project will be a model for employing clean energy production to support environmental education, conservation, and restoration efforts in the Florida Keys and beyond.

Keywords: *Hydrokinetic, Green Hydrogen, Green Oxygen, Energy, Sustainable*

Introduction

To realize the Paris Agreement¹ goal for net-zero CO₂ emissions by 2050, it is critical to transition energy production towards clean, reliable, predictable, and sustainable renewable energy production for all forms of transportation (i.e., cars, trucks, aviation, and shipping) as well as other industries that currently rely on fossil fuels.

Recent advances in hydrogen fuel cell technology and hydrogen internal combustion engines (H₂ICE), combined with advances in water electrolysis technology and H₂ fuel production/storage, foster a

¹The Paris Agreement, United Nations Climate Change, <https://unfccc.int/process-and-meetings/the-paris-agreement>.

realistic pathway for green H₂ to be used for energy production to support transportation and industrial energy needs². It represents the best technology available to achieve the Paris Agreement goal.

The US Department of Energy (DOE) Hydrogen and Fuel Cell Technologies Office, and other global organisations consider hydrogen as the fuel of the future. To achieve net-zero CO₂ emissions by 2050, it is critical to convert all forms of transportation to hydrogen. Regardless of whether hydrogen is being used to power a fuel cell or as a fuel in an H₂ICE, the only emissions are water vapor. Because H₂O can be recycled and split into H₂ and O₂ repeatedly, it is the perfect solution for a carbon-free future if we use green electricity to split the molecules.

On June 5, 2023, the DOE released the National Clean Hydrogen Strategy and Roadmap³; a comprehensive framework for accelerating the production, processing, delivery, storage, and use of clean hydrogen. It intends to reduce US greenhouse gas emissions to half of 2005 levels by 2030, achieve 100% carbon-free electricity by 2035, and achieve net-zero CO₂ emissions by 2050.

Recognising the need for clean energy, the U.S.-based company, Hydrokinetic Energy Corp (HEC) designed, developed, analysed, optimised, and patented a high-efficiency marine electrical energy generation hydrokinetic turbine. This patented technology received the "Patents for Humanity" award from the United States Patent and Trademark Office (USPTO) on 3rd December 2024.

The College of the Florida Keys (CFK) partnered with HEC to develop a pilot project that utilises HEC's patented hydrokinetic turbine technology to demonstrate sustainable fuel production with zero carbon dioxide (CO₂) emissions and uses that clean fuel to power educational and research facilities at CFK. This one-of-a-kind pilot project intends to provide "proof of concept" for an innovative clean energy pathway directly from the producer to the end user.

The Pilot Project: Overview

The project will deploy a floating platform equipped with four patented HEC hydrokinetic turbines each with a 1.5 m rotor diameter and fortified with: (1) flow acceleration technology that increases energy extraction by up to 300%, and (2) wildlife and debris excluders (WDE) that not only protects marine life and the turbines but also increase energy extraction by an additional 5-10%. Located approximately 35 km south of Key West, Florida (USA) in the Gulfstream, these innovative hydrokinetic turbines will revolutionise the hydrokinetic energy industry by allowing the most efficient extraction of energy from one of the world's most powerful ocean currents. The four HEC turbines combined will produce approximately 48 kW of continuous electrical energy that will power two reverse osmosis (RO) desalination units. The RO units will feed freshwater into two onboard electrolysis units that split water (H₂O) molecules into "green" hydrogen (H₂) and "green" oxygen (O₂). The term "green" is used because the power source used to split the molecules is hydrokinetic (i.e., a green renewable energy) as opposed to "black" or "grey" hydrogen made from burning fossil fuels. The production of green H₂ fuel also fosters offshore energy production by circumventing the deployment of subsurface

²Turner, J.W.G. Future technological directions for hydrogen internal combustion engines in transport applications. *Applications in Energy and Combustion Science*, 2, no. 100302 (2025), <https://doi.org/j.jaecs.2024.100302>.

³U.S. National Clean Hydrogen Strategy and Roadmap, U.S. Department of Energy, 2023, <https://www.hydrogen.energy.gov/library/roadmaps-vision/clean-hydrogen-strategy-roadmap>.

electric power cables to transfer energy to the end user. The green H₂ fuel will be shipped onshore to CFK to be used as fuel for commercially available hydrogen power generation, producing pure H₂O as the only exhaust. The green O₂ will be used to oxygenate aquaculture facilities to sustain marine organisms being grown for education, research, and environmental restoration (i.e., coral restoration) at the Southernmost Marine Aquaculture Research & Training (SMART) Centre at CFK (Figure 1).

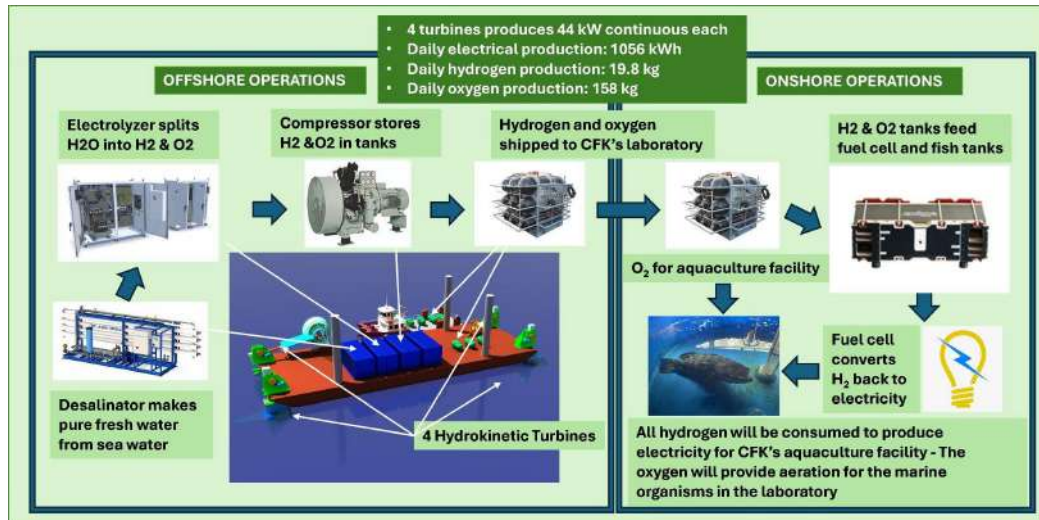


Figure 1: A flow chart of offshore energy production and conversion to transportable green hydrogen and oxygen to be utilized for onshore energy consumption and aquaculture.

This pilot project is intended to be a pioneering effort and model for employing clean energy production to support environmental education, conservation, and restoration efforts in the Florida Keys and beyond.

The Pioneering Turbine Technology

Although the Gulf Stream is one of the most powerful oceanic currents on earth, it flows relatively slowly (6.4 kph or 1.8 m/s). This makes it unsuitable for traditional hydrokinetic current-energy-converters (CECs) because the density, viscosity, and frictional forces of seawater inhibit the speed at which the blades spin and limits the effective length of the turbine blade designs. This is why most traditional CECs are shaped like wind turbines with short, stout hydrofoil blades (Figure 2) and deployed in very fast ocean currents (e.g., Orkney Scotland at 14.4 kph or 4 m/s).



Figure 2: An image of a traditional hydrokinetic CEC array. Notice the short turbine blades relative to a traditional terrestrial wind turbine.

HEC's innovative hydrokinetic turbine overcomes this flow velocity limitation by focusing the horizontal axial hydrodynamic flow and features several novel design elements NOT found in other state-of-the-art hydrokinetic turbines, including:

1. Flow acceleration technology (FAT) enabled by the synergistic effect between the hydrofoil-shaped rotor blades attached to a hydrofoil-shaped centre hub encased in a hydrofoil-shaped accelerator shroud and surrounded by a hydrofoil-shaped diffuser. This design increases the flow-through velocity up to 300%, resulting in up to 8x increase in turbine power output (calculated using the formula $KE = \frac{1}{2} mv^2$, where KE is kinetic energy).
2. Low-cost construction by employing additive/subtractive manufacturing using the newest 3-D printing materials in very large robotic 3-D printers. This eliminates 70% of labour cost, resulting in the lowest cost per turbine on the market with the lowest Levelized Cost of Electricity (LCOE). Carbon fibre reinforced polyethylene terephthalate glycol (PETG) is used to manufacture the turbines. This material is 100% recyclable at the end of the 25-year life cycle.
3. Low-cost operation and maintenance because of floating installation, which allows the turbines to be brought to the surface quickly and easily for cleaning, maintenance, or repair.
4. Unidirectional flow feature that provides up to 30% higher efficiency than bidirectional turbines.
5. No shaft or gears because of an annular generator, which reduces friction losses during power take-off (PTO),
6. A flow-through accelerating wildlife and debris excluder (WDE) (Figure 3A - CAD drawing with WDE, Figure 3B - prototype CEC with WDE in the lab, Figure 3C and Figure 3D - prototype with WDE being tested from a vessel in the ocean):
 - a. protects wildlife from being harmed
 - b. protects the turbine from debris
 - c. induces a pre-swirl of the water, enhancing performance by increasing flow-through velocity and energy output by 5-10%
 - d. constitutes a transformational solution that positively impacts the capability of extracting energy at low-flow velocities.

To date HEC tested and validated 6 reduced scale prototypes, including a turbine with 0.375 m rotor (Prototype No.6) capable of producing 1.78 kW continuous electrical power. *In-situ* ocean testing of these prototypes confirmed results obtained during computational fluid dynamic (CFD) modelling and demonstrated that the design is scalable and works equally efficiently at all sizes tested. Prototype No.7 (.075 m rotor) is currently in production and scheduled for testing and validation during fall 2025. It can produce 7.1 kW of continuous electrical power. Finally, the HEC turbine proposed for the pilot project (Prototype No.8) will have a 1.5 m rotor and be capable of 12 kW of continuous electrical power. For the pilot project, four of these turbines are proposed with an estimated gross power output of 48 kW continuous electrical power.

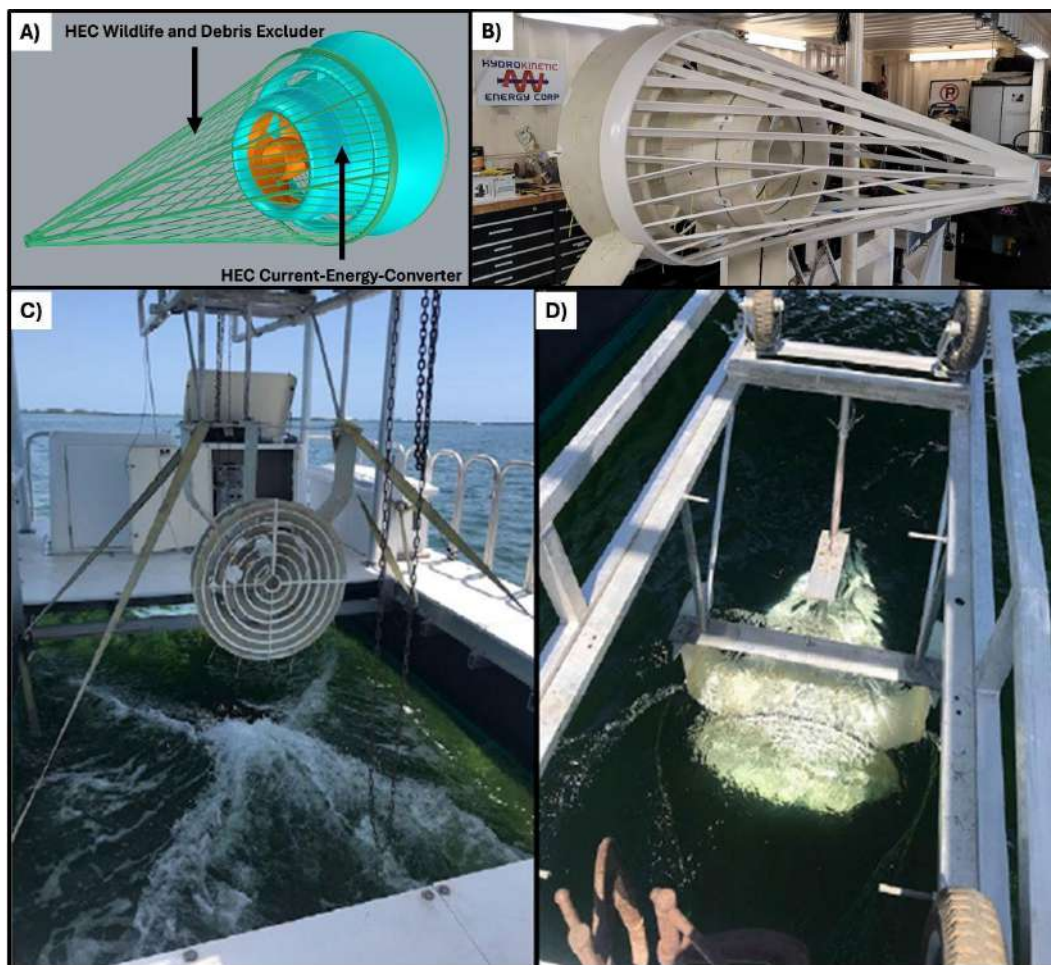


Figure 3: (A) CAD rendering of the HEC current-energy-converter (CEC) with wildlife and debris excluder (WDE), (B) prototype No.6 CEC with the WDE in the lab at HEC, (C) HEC prototype No.6 ready for testing at sea, (D) HEC prototype #6 deployed during sea trials.

The Pilot Project: Offshore Production

The primary objective focuses on the production of green H_2 and green O_2 utilising renewable hydrokinetic electric power harvested from one of the most powerful, reliable, and predictable renewable energy resources on earth, the Gulfstream.

The pilot project incorporates a large floating platform equipped with four HEC hydrokinetic turbines. All HEC turbines (Prototype No.8) combined will produce 48 kW gross continuous electrical output, of which 4 kW of electricity will be used to desalinate the seawater for electrolysis and compress the green H_2 and green O_2 into storage tanks at 700 bar or 10,152 psi. The remaining 44 kW of electric power will be used for the electrolysis of water, producing 19.8 kg green H_2 /day (enough fuel to power approximately 20 average U.S. households per day) and 158.8 kg green O_2 /day. The gases will be shipped to CFK for energy production (green H_2) and providing life support (green O_2) for organisms at the SMART Centre. H_2 fuel can also be stored for future electric generation in the event of a power outage (e.g., a hurricane).

Pilot Project: End User

CFK has a robust marine aquaculture research and training program at the SMART Centre. The SMART Centre currently uses electricity provided by the local energy grid and powers infrastructure to support aquaculture operations. The green H₂ produced offshore will be used to offset the grid energy, while the green O₂ will be used for life-support systems at the SMART Centre. CFK intends to incorporate the pilot project into the renewable energy training program and establish a Centre of Excellence for Additive Manufacturing using 3-D printers that will manufacture the HEC Prototype No. 8 turbines.

Future Markets and Broader Impacts

Liquid oxygen (LOX) is the primary component in rocket fuel (73%) to launch spacecraft into orbit. NASA, SpaceX, and Blue Origin use tremendous amounts of LOX. Therefore, green O₂ will help to reduce the carbon footprint of space exploration.

Conclusion

This pilot project demonstrates a transformative proof of concept for a next-generation approach to marine renewable energy. By integrating advanced current energy converter (CEC) design with proprietary flow acceleration technology, this system is capable of harnessing mechanical energy from powerful ocean currents—such as the Gulf Stream—to produce clean, renewable hydrogen (H₂) fuel at scale.

Unlike conventional CEC systems, which are limited by low-velocity currents and inconsistent performance, HEC turbine technology is specifically engineered to operate efficiently in a broader range of ocean conditions. This breakthrough significantly expands the viable geographic footprint for marine energy deployment and unlocks previously inaccessible energy resources.

Equally important, on-site hydrogen production eliminates the need for subsea power transmission cables, reducing infrastructure costs while minimizing environmental disruption to sensitive marine ecosystems. The result is a more scalable, cost-effective, and environmentally responsible pathway to offshore energy generation.

This project represents a critical first step toward establishing a new, sustainable energy industry—particularly in the Florida Keys—with the potential for global replication. By enabling the large-scale production of zero-carbon fuel, this technology directly supports the transition away from fossil fuels, contributes to meaningful reductions in CO₂ emissions, and advances progress toward meeting the goals of the Paris Agreement.

Acknowledgements

We gratefully acknowledge the support and contributions of the following organizations and individuals:

1. The United States National Hydropower Association (NHA) and the United States Department of Energy's Testing Expertise and Access to Marine Energy Resources (TEAMER) Program for their essential funding and support of this technology's development.
2. The American Bureau of Shipping for its expertise and guidance in optimizing turbine design and performance.
3. Mr. Ronald Barret for his valuable assistance during the initial prototype testing phase.

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- U.S. National Clean Hydrogen Strategy and Roadmap. 2023. U.S. Department of Energy <https://www.hydrogen.energy.gov/library/roadmaps-vision/clean-hydrogen-strategy-roadmap>.

Chapter 35

Mixed Waste Plastics Derived Composites for Flood and Hurricane Protection

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Abstract

This paper investigates sustainable hybrid composites made from waste mixed plastics (wMP), waste glass fibres (wGF), and recycled carbon fibres (rCF), as viable alternatives for construction materials, including C-sections, hurricane/flood-resistant structures. Two lay-up configurations with varying rCF and wGF contents were evaluated through tensile, compressive, and flexural tests, revealing superior mechanical performance in specimens with higher rCF content. Three thermoformed hybrid C-sections containing approximately 15 vol% rCF, 10 vol% wGF, and 75 vol% wMP were manufactured and tested under axial compression, failing mainly by some delamination and crushing; their weight-specific load capacity exceeded that of comparable ultra-thin-walled steel C-sections by nearly 95%. High-velocity impact tests resisted windborne debris at velocities of 103–125 m/s, outperforming Australian and New Zealand standards and showing superior or comparable ballistic resistance to conventional plywood. These results highlight the potential of repurposed waste materials to be used as structures to benefit society and save human lives.

Keywords: *Waste mixed plastics, Waste glass fibres, Recycled carbon fibres, C-section, Hurricane-resistant panels.*

Introduction

Plastic waste is a major contributor to global landfill volumes, posing significant environmental, economic, and social challenges. Designed for single-use applications for items like food wrappers, containers, and plastic bags have short life cycles but persist in the environment for centuries. They are generally not recycled due to their low cost and low performance. Transforming such wastes or any recycled plastics into sustainable construction materials offers a promising solution, enabling landfill reduction, resource conservation, lower carbon emissions, cost-effectiveness, and the promotion of a circular economy.

By combining waste mixed plastics (wMP) from packaging with reinforcements like waste glass fibre (wGF) and recycled carbon fibre (rCF), it is possible to create durable composite materials with high

strength-to-weight ratios and excellent corrosion resistance. These composites not only minimise batch-to-batch variability in wMP but also provide tailored performance for diverse applications. For instance, they can be formed into structural C-sections, impact-resistant transport panels, or flood barriers, enhancing both structural integrity and human safety in disaster-prone regions.

This study investigates hybrid laminates made from wMP, wGF, and rCF to address structural needs and sustainability goals. The plastic packaging film waste was first subjected to float-sink separation to segregate the wastes that were lighter than water. These low-value, lightweight mixed plastic wastes were used in their as-received form to reduce further segregation costs and environmental impact. Flat laminates with approximately 15 vol% rCF, 10 vol% wGF, and 75 vol% wMP were manufactured and then thermoformed into C-sections followed by testing under axial compression. These sections demonstrated exceptionally promising performance. Additionally, high-velocity impact testing simulating hurricane conditions revealed that these composites exceeded Australian/New Zealand standards and outperformed conventionally used plywood, highlighting their potential in critical infrastructure applications.

Results and Discussion

A: C-Section

A.1: Manufacturing flat laminates

Extensive research was carried out to characterise wMP¹, develop wMP-wGF prepregs (wMP-coated wGF nonwoven mats) (Figure 1), and manufacture flat laminates comprising wGF plies, wGF-wMP prepreg plies, and recycled carbon fibre/maleated polypropylene (rCF-MAPP) based nonwoven mats². The rCF-MAPP nonwoven mat was procured from the market³.



Figure 1: Waste mixed plastics (wMP), waste glass nonwoven mat (wGF), and wMP-coated wGF mats.

¹Kit O'Rourke et al., "Diverted from Landfill: Reuse of Single-Use Plastic Packaging Waste," *Polymers*, 14 (2022): 5485; <https://doi.org/10.3390/polym14245485>.

²Kit O'Rourke et al., "Diverted from landfill: Manufacture and characterisation of composites from waste plastic packaging and waste glass fibres," *Sustainable Materials and Technologies*, 39 (2024): e00851, <https://doi.org/10.1016/j.susmat.2024.e00851>.

³Gen 2 Carbon, "Home," accessed July 18, 2025, <https://www.gen2carbon.com/>.

The lay-up configuration consisted of 16 wGF plies, 2 wMP-wGF prepreg plies, and 6 rCF-MAPP plies (Figure 2). The laminates were produced using compression moulding at 200°C under 18 bar pressure for 20 min. This hybrid laminate is designated as wGF-wMP/rCF-MAPP.

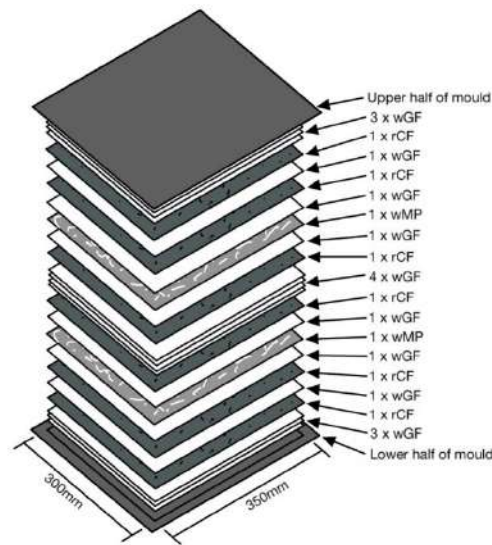


Figure 2: Exploded diagram of lay-up stacking sequence for laminate configuration.

A.2: C-Section shaping

The flat wGF-wMP/rCF-MAPP laminates (cut into 300 × 220 mm) were shaped (thermoformed) into C-sections by using a custom-made metal mould (see Figure 3) as detailed in our published paper⁴.

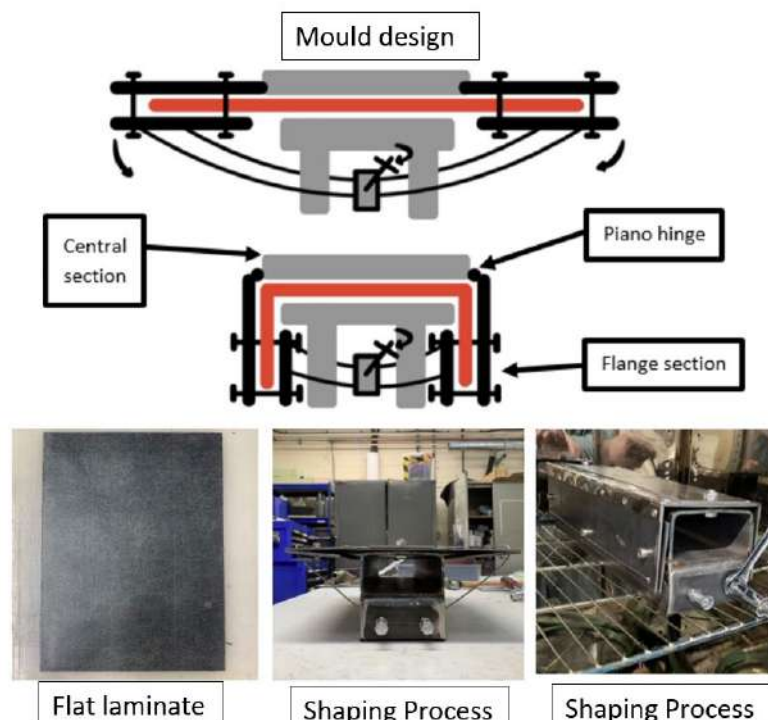
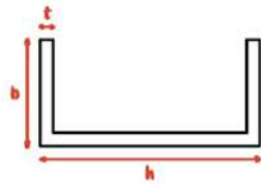


Figure 3: C-section mould: Step-by-step thermoforming of a C-section and final C-section.

⁴Danijela Stankovic et al., Developing hybrid C-sections from waste and recycled composite materials, *Sustainable Materials and Technologies*, 41 (2024): e01102, <https://doi.org/10.1016/j.susmat.2024.e01102>.

Three C-sections were produced, namely CS1, CS2, and CS3 (an extra step in the thermoforming process was used in this case only), and their dimensions are given in Table 1. It is worth noting that CS1 is slightly shorter in length due to an accidental crush of the specimen's edge. Nevertheless, this incident did not impact the results, as discussed in the following sections.

Table 1: Dimensions and weight of the three C-sections produced.



C-section	Length, L (mm)	Flange, b (mm)	Depth, h (mm)	Thickness, t (mm)	Weight (Kg)
CS-1	189	54	116	5.0	0.20
CS-2	303	54	116	4.8	0.33
CS-3	301	53	117	4.9	0.32

A.3: Axial compression testing

For axial compression testing of C-section specimens, a DSLR Canon EOS 5D Mark IV camera was used to monitor the strain field and images were captured at intervals of 2 seconds. The centroid of the C-sections was aligned with the centre of each platen to ensure concentric axial loading, and the crosshead displacement was set to 1.3 mm/min according to ASTM D6641M-21 standard test method.

A.4: Axial compression properties of C-sections

The load versus displacement curves of CS1, CS2, and CS3 are shown in Figure 4. Prior to failure, the C-sections displayed quite similar behaviour, characterised by nonlinear buckling. CS1 and CS2 demonstrated a drop in the load soon after the ultimate load was reached, whereas CS3 was able to retain the load after the peak load was reached.

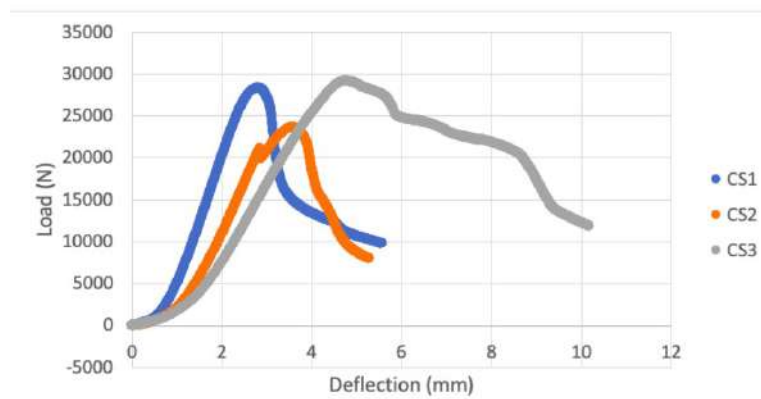


Figure 4: Load versus displacement curves of the C-section specimens (CS1/CS2/CS3).

The load retention and slightly higher peak load of CS3 (29.14 kN) compared to CS1 (28.33 kN) and CS2 (23.61 kN) may be attributed to the reduction of internal stresses induced by deformation during the thermoforming stage. This suggests that additional stages during thermoforming could enhance the load and strength capacity. These C-sections outperformed many virgin material-based C-sections as reported in our published paper.

Producing C-sections with short fibre reinforcements can be beneficial compared to unidirectional continuous fibres or tightly woven mat-reinforced composites. As short fibres exhibit greater drapeability, particularly when integrated into a ductile thermoplastic matrix, they prevent significant damage. The creep in such matrices is reduced due to the presence of the fibres.

B: Hurricane-resistant Panels

B.1: High velocity impact testing

High-velocity impact tests were conducted using a gas barrel gun with a pressure capacity of up to 10 bar (≈ 200 m/s), shown in Figure 5⁵. Specimens were clamped between plywood frames with a central square opening (100 x 100 mm) and positioned on a height-adjustable wheeled table 2.58 m from the gun nozzle. An 8 mm, 2 gr steel ball bearing was fired at varying speeds onto the specimen surfaces (based on ASTM E1886). Impact regions followed a triangular pattern as per ASTM E1996.

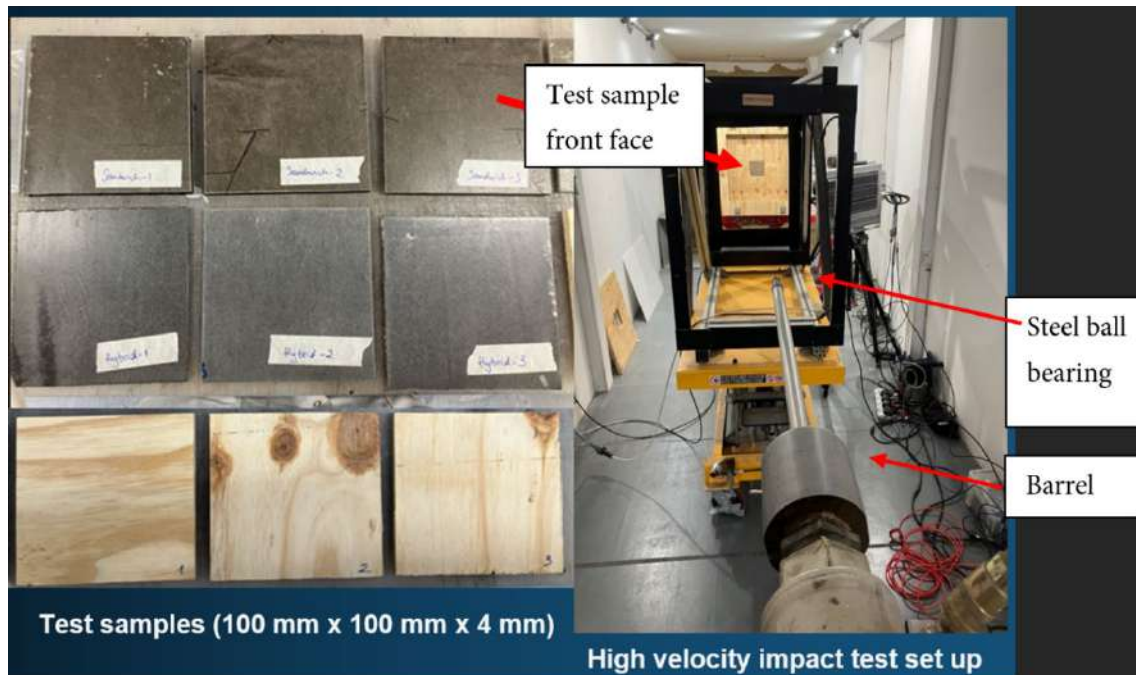


Figure 5: High velocity impact test samples and test setup.

The ballistic limit (V_{50}) and initial kinetic energy of the five different specimen types are presented in Table 2 and Figure 6, respectively. The polycarbonate (PC) specimens experienced the highest ballistic limit despite being the thinnest specimens⁶. The results show that waste-based laminates can offer an effective solution for ballistic impacts as they can resist velocities higher than the typical design wind velocities used in the AS/NZ standards (70-80 m/s).

Table 2: High velocity impact test results for various samples.

Laminate Type		Average Thickness (mm)	Ballistic Limit V_{50} (m/s)
wGF-wMP/rCF-MAPP	Hybrid laminate (C-section made with the same laminate)	5.56	125.44
wGF-wMP laminate	Waste glass and waste mixed plastics	4.31	103.51

⁵D.J. Goode & Associates Ltd, <https://djgoode.com/>.

⁶S. C. Wright et al., "Ballistic impact of polycarbonate—An experimental investigation," *International Journal of Impact Engineering*, 13 (1993): 1–20. [https://doi.org/10.1016/0734-743X\(93\)90105-G](https://doi.org/10.1016/0734-743X(93)90105-G).

Table 2: Continued.

Laminate Type		Average Thickness (mm)	Ballistic Limit V_{50} (m/s)
wGF-wMP skins, crosslinked polyethylene foam core	Sandwich	8.94	78.33
Plywood	From market	9.43	96.58
Polycarbonate	From market	2.97	>130

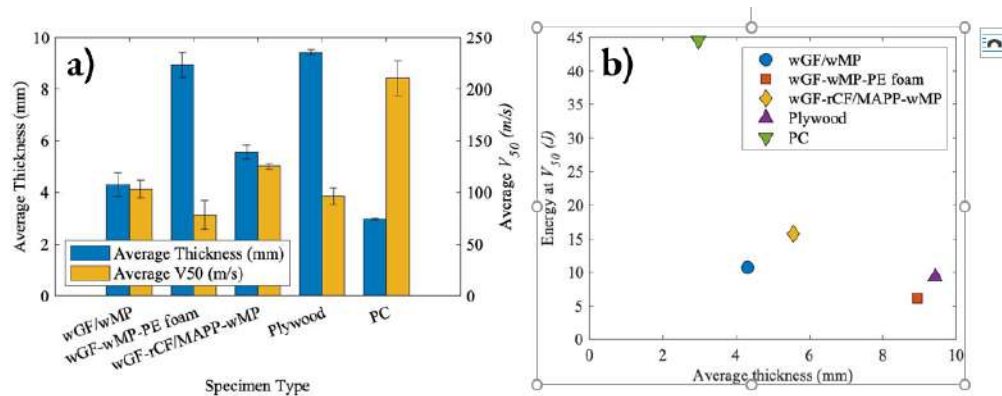


Figure 6: (a) Average thickness and ballistic limit (V_{50}) for each specimen type along with standard deviation values; (b) Initial energy versus average thickness of each specimen type.

Figure 7 shows that all specimens were perforated except the wGF-wMP/rCF-MAPP hybrid one ($V_{50}=125$ m/s). For the plywood specimens, perforation occurred at an impact velocity of 119 m/s. Both the front and rear faces showed a clear hole, and as the ball bearing exited, plywood pieces were ejected from the rear face (Figure 7).

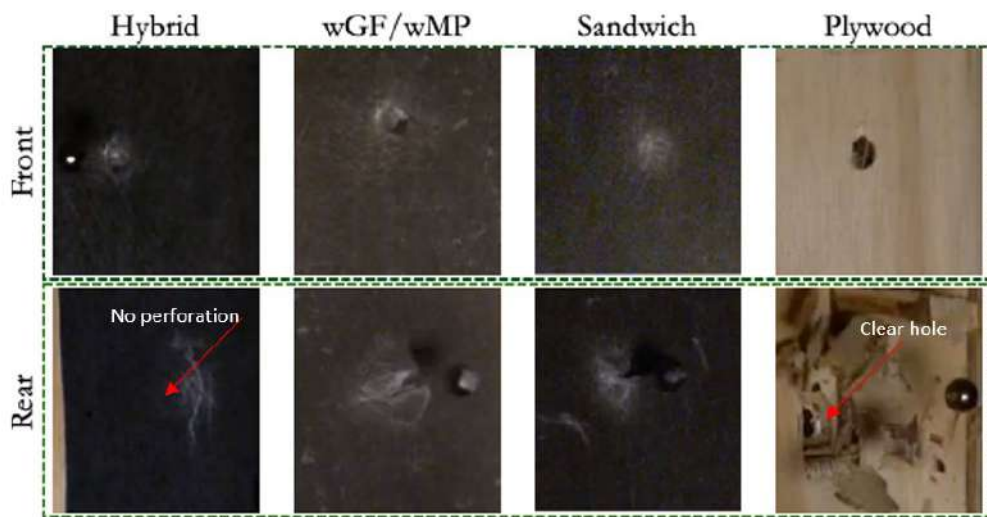


Figure 7: Surfaces of the front and rear faces of the tested specimens following impact.

Prototypes Planned:

Once funding is available, these laminates would be made into the following prototypes:

- 1) Single slot-in flood barrier panels of approximate size (0.9m wide x 0.3m high x suitable thickness) in collaboration with Flood Control International, UK⁷.
- 2) Hurricane-resistant panels (approximate size 1m x 1m x thickness to decide) will be produced, and a tornado test will be carried out at an external institute in Italy⁸.

Conclusion

This technology will serve a dual purpose:

- 1) Divert low-value plastic waste and glass fibre waste from landfill into useful product forms and lock them for a long period of time.
- 2) Save human lives in disaster-prone areas at a low cost/easy availability. These can be locally made using local plastic waste.

Acknowledgements

The authors would like to acknowledge the funding from the CIMComp EPSRC Future Composites Manufacturing Research Hub (Grant Ref: EP/ P006701/1) and EPSRC Impact Acceleration Award (IAA) (grant reference EP /X525698/1). The authors are grateful to Johns Manville and PALTECH for supplying the materials and expertise.

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⁷Flood Control International. *The Water Stops Here*®. Accessed July 18, 2025 <https://www.floodcontrolinternational.com>.

⁸Construction Technologies Institute (ITC), Consiglio Nazionale delle Ricerche. About Us. Accessed July 18, 2025 Construction technologies institute (ITC) | Consiglio Nazionale delle Ricerche.

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Chapter 36

Leveraging AI-coupled Digital Twin Ecosystems for all Sustainable Development Goals in the Built Environment

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Abstract

This chapter presents the results and outcomes of FRESH-BIM/FRESH-DT, two internationally co-funded, awarded, and published joint projects, addressing urgent inefficiencies in global construction practices—producing 32% of global energy and carbon emissions, 40% waste, and >80% time/cost overruns—while also tackling often-overlooked social, biodiversity, and governance challenges. As such, this paper discusses utilising innovative technological advances to address these urgent problems in the built environment and heritage while aligning with the 17 UN Sustainable Development Goals (SDGs). Opportunities of utilising digital-twin (DT) and AI machine-learning functionalities in tandem are first demonstrated, to enhance different buildings' sustainable performance aspects throughout different lifecycle phases, including energy/carbon reduction, improving users' indoor microclimate, building materials' circularity, reducing waste, optimising design/construction/operations time, cost, and quality processes. The approach considers broader impacts on social equity, biodiversity, and governance, aligning with the SDGs. This chapter then delves into implementation details of the FRESH-BIM/FRESH-DT projects performed in collaboration with government, academic, and industry bodies in the UK and Egypt, focusing on revitalisation of national heritage assets, to create a positive impact on increasing national tourism and contributing to GDP growth. The projects created an AI/DT analytics ecosystem with 5 deliverables, including a new classification system and an expert system for renovation of heritage assets, aligning with all UN SDGs, and on the route for national-scale adoption.

Keywords: *Digital Twin, Artificial Intelligence, Built Environment, Sustainable Development Goals, Heritage*

Introduction

The built environment is a major contributor to global sustainability challenges as a resource-intensive sector accounting for >32% of global energy consumption 34% of global CO₂ emissions¹, with only 16% of construction projects finishing on time/budget, and waste levels reaching 40%² due to

¹United Nations Environment Programme and Global Alliance for Buildings and Construction, *No Just Another Brick in the Wall: Global Status Report for Buildings and Construction 2024/2025*, 2025 <https://wedocs.unep.org/20.500.11822/47214>.

²Cuéllar-Reyes et al.,

“Causes of Cost and Time Overruns in Construction Projects and Methodologies for Their Mitigation.”

inefficiencies/rework. These inefficiencies are exacerbated by fragmented workflows, poor data integration, and delayed reactive decision making. As urbanisation accelerates and climate targets intensify, the need for intelligent/adaptive/sustainable construction practices becomes vital as a resolution. Innovative technologies, for example, Digital Twin (DT) and Artificial Intelligence (AI) offer transformative potential for these challenges. When used collectively, they enable real-time monitoring, predictive analytics, and lifecycle optimisation across design/construction/operational phases, supporting both technical performance and broader sustainability goals.

DT and AI Synergy Across Lifecycle Phases

A DT is a dynamic, virtual representation of a physical asset/system/process. It integrates data from sensors, building information modelling (BIM) data, and operational systems to simulate/analyse/optimise performance via diagnostics. Enhanced with AI, DTs become intelligent systems learning from historical and real-time data, enabling pattern recognition, anomaly detection, predicting outcomes, forecasting, decision-making, and recommending interventions. Together, they improve building performance, indoor microclimate, quality processes, and reduce waste/time/cost. This approach also considers broader impacts on social equity, biodiversity, and governance, aligning with all 17 UN Sustainable Development Goals (SDGs)³.

- **Design phase:** DT can simulate multiple design scenarios based on legacy or live Internet-of-Things (IoT) sensor telemetry data. AI algorithms can then generate multiple design alternatives to optimise energy/carbon performance, daylight penetration, thermal comfort, assess material usage/circularity, and cost constraints. AI-coupled DT enable scenario-testing, helping evaluate the impact of design choices on long-term sustainability⁴.
- **Construction phase:** AI can detect anomalies, forecast delays, and optimise resource allocation. DTs provide live dashboards of site activities, enabling proactive logistics, safety, and quality management. This reduces waste and improves stakeholders' coordination. Zahedi et al.⁵, found that DT applications in construction significantly reduce material waste and improve compliance with sustainability indicators to align with the SDGs.
- **Operational phase:** AI-enhanced DTs support predictive maintenance, energy optimisation, and occupant comfort. IoT sensors embedded in buildings feed data into DTs, which uses machine learning to identify inefficiencies and recommend adjustments. For example, in New York City, AI-paired DTs are used to comply with Local Law 97, which caps emissions from over 40,000 buildings. These systems track energy/water/waste/air quality data, enabling building owners to reduce emissions and improve ESG reporting⁶.

2 7th International Congress on Project Management and Engineering, Donostia-San Sebastián, July 10–13 (2023) http://dspace.aepro.com/xmlui/bitstream/handle/123456789/3362/AT01-055_23.pdf?sequence=1.

³Ehtsham et al., "AI_Powered_Advanced_Technologies_for_a_Sustainable_Built_Environment: A_Systematic_Review on_Emerging_Challenges," *Sustainability* 17, no. 17 (2025): 8005 <https://doi.org/10.3390/su17178005>.

⁴Ehtsham et al., "AI_Powered_Advanced_Technologies," 8005.

⁵Zahedi et al., "Digital_twins_in_the_sustainable_construction_industry," *Buildings* 14, no. 11: 3613 <https://doi.org/10.3390/buildings14113613>.

⁶Ehtsham et al., "AI_Powered_Advanced_Technologies," 8005.

Circularity and Waste Reduction

With construction accounting for 40% of total global waste, DTs can track material flows, origin, composition, and reuse potential/opportunities, supporting circular economy practices and material passports. AI algorithms can then classify/select low-impact carbon-footprint materials, predict their end-of-life scenarios, waste/reuse types, and optimise deconstruction strategies for waste minimisation. Pierzchlewicz et al. (2025)⁷, found circular architecture strategies and lifecycle assessments (LCA) most effective when integrated with DT/AI systems. Linking with BIM and building management systems data, can assess embodied/operational carbon, enabling more accurate sustainability benchmarking.

Indoor Microclimate, Health, Social Equity, Biodiversity, and Governance

Indoor environmental quality is critical for occupant health, well-being, and productivity. AI-powered DTs can monitor temperature/humidity/air quality/lighting, adjusting systems in real-time to maintain optimal conditions. In smart buildings, these systems can reduce energy consumption by 30% while improving thermal comfort⁸. Löfstad Castle, Sweden DT was created for preventive conservation and operational sustainability to monitor/manage indoor climate conditions threatening preservation of its collections. AI-driven analytics identified high-humidity zones and guided installation of vapor barriers and energy-efficient ventilation strategies.⁹ Beyond technical performance, DT/AI can support social sustainability. Analysing/simulating user behaviour, accessibility, movement, occupancy, and demographic data can identify underserved communities, guide equitable resource distribution, and ensure inclusive environments. DT/AI also drives impact in governance, providing transparent, data-driven insights, supporting policymaking and stakeholder collaboration¹⁰.

FRESH-BIM and FRESH-DT: AI-Driven DT Ecosystems for Sustainable Heritage and Construction Transformation

The FRESH-BIM/FRESH-DT projects are two internationally co-funded initiatives, led by Dr. Noha Saleeb (Middlesex University, UK) to address the urgent renovation and sustainability challenges in the Egyptian heritage sector by leveraging AI-enhanced DT ecosystems to restore/optimize heritage assets, hence contributing to tourism and national GDP. These were published on the EAUC UN_SDG Accord website as impact case studies aligning with all UN SDGs and were awarded the Green Gown UK/Ireland Sustainability Champion Award 2024. The project was funded through institutional links grants from the British Council UK and the Science and Technology Development Fund (STDF) Egypt.

⁷Pierzchlewicz et al., “Recent Research on Circular Architecture: A Literature Review of 2021–2024 on Circular Strategies in the Built Environment,” *Sustainability* 17, no. 17 (2025): 7580 <https://doi.org/10.3390/su17177580>.

⁸Díaz Caselles et al., “Sustainability Performance in OnSite Construction Processes: A Systematic Literature Review,” *Sustainability* 16, no. 3 (2024): 1047 <https://doi.org/10.3390/su16031047>.

⁹Mazzetto Silvia, “Integrating Emerging Technologies with Digital Twins for Heritage Building Conservation An Interdisciplinary Approach with Expert Insights and Bibliometric Analysis,” *Heritage* 7, no. 11: 6432–6479 <https://doi.org/10.3390/heritage7110300>.

¹⁰Ehtsham et al., “AI Powered Advanced Technologies,” 8005.

This involved a consortium of academic/government/industry associated partners, including Cairo University, Ministry of Antiquities Egypt, Historic Environment Scotland, BuroHappold UK, Karnak Egypt. These collaborations enabled the projects to operate across both the UK and Egypt, focusing on heritage restoration, sustainable construction, and digital innovation.

Results and Discussion

Project Objectives: The overarching goal of FRESH-BIM/FRESH-DT was to create a scalable AI + DT + Analytics-Ecosystem to achieve the following objectives:

- Improve sustainability performance across the building lifecycle
- Enable intelligent renovation and operations of heritage assets
- Align with all 17 UN SDGs

Case Study: The flagship application of the ecosystem was restoration of the Toson Palace (Cairo), a nineteenth century heritage site with failing structural elements due to previous fires, deteriorating unmaintained spaces, corroding building services, and wildlife infestations (Figure 1). FRESH-BIM/FRESH-DT applied AI and DT to restore this heritage site, integrating structural analysis, social simulations, and predictive maintenance. The project further aligns with all 17 SDGs, as explained subsequently, and is currently being scaled nationally.

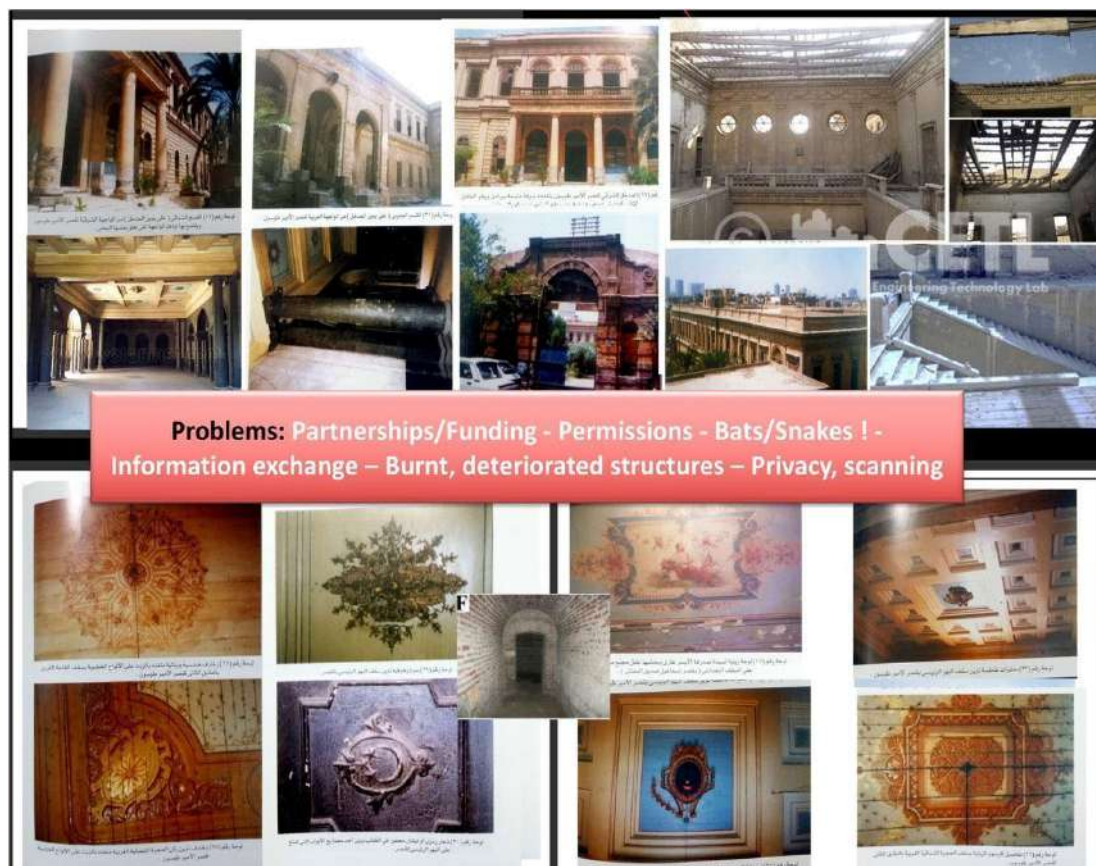


Figure 1: Toson Palace condition showing internal damaged status.

Outputs: The ecosystem produced **five key deliverables**:

1. *Heritage classification system*: A novel heritage asset-types' taxonomy, to guide renovation strategies and policy decisions. This was adopted by experts working on Westminster Palace and Big Ben Clock Tower renovations in London.
2. *Structural analysis framework*: Integrated 3D laser scanning, seismic analysis, and parametric modelling to assess building integrity and simulate environmental impacts.
3. *Expert renovation system*: AI-driven decision-support tool for optimising restoration workflows, material reuse, and cost/time efficiency.
4. *Social VR/AR simulations and analytics platform*: To simulate user behaviour, accessibility, occupancy patterns, and ensure inclusive design and cultural engagement.
5. *Real-time visual analytics platform for predictive maintenance*: Enabled proactive monitoring of building systems, reducing lifecycle costs and improving operational sustainability.

Project workflows started by conducting a comprehensive 3D laser scan of the whole building and surrounding estate with varying precision tolerances. Challenges included: permissions required from the Ministry of Antiquities and the surrounding school to scan adjacent walls, danger from bats/snakes' basement infestation, risk of collapse of stairs/roofs damaged by fires. Upon converting all point clouds to BIM models, the AI/DT system architecture was implemented:

- Sixteen sensor types (Figure 2) were installed in spaces with diverse functions/sizes/floors to capture indoor environmental conditions in both used/unused spaces, mobility, and occupancy in public user spaces, water/pollution/structure conditions.

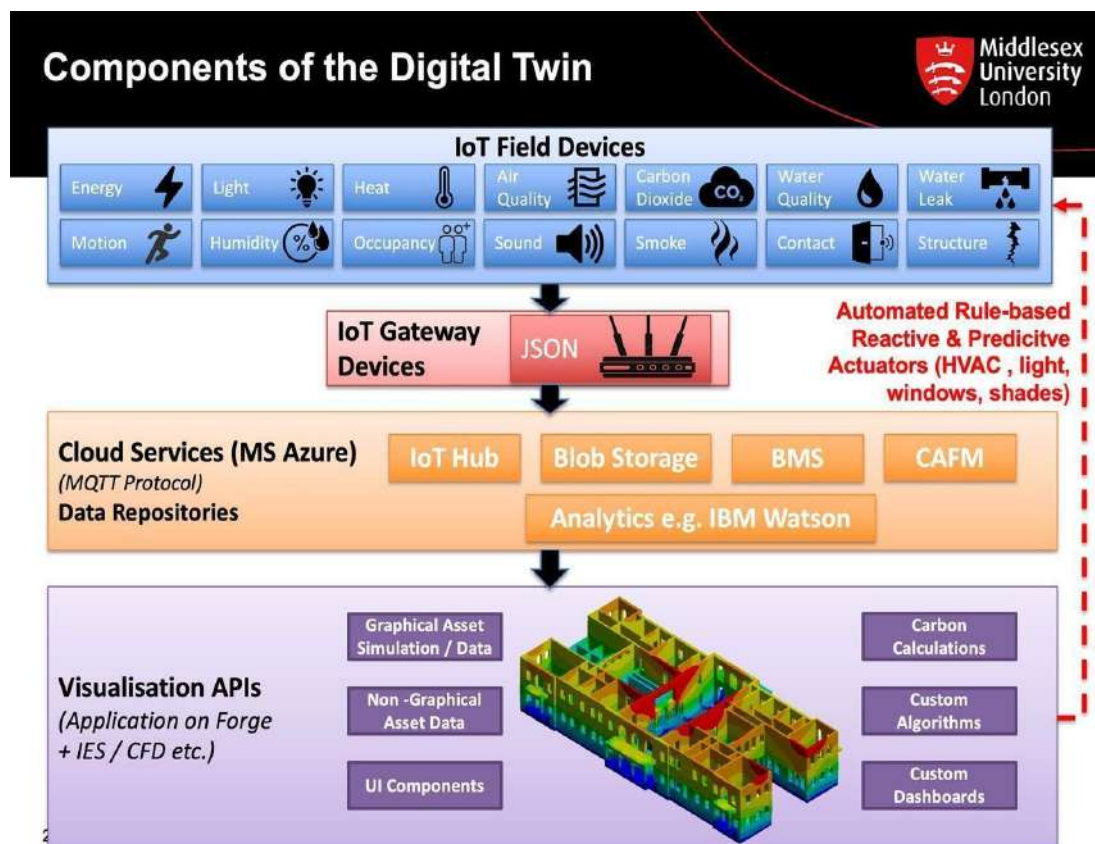


Figure 2: AI-coupled DT architecture.

- These were connected via JSON gateway devices to MS Azure cloud services and archival data repositories, connected to the BIM models to create the DT.
- AI machine-learning algorithms (Figure 3) and visualisation dashboards were created to analyse the data, predict future conditions, space usage, and recommend solutions for enhancing the spaces' performance.

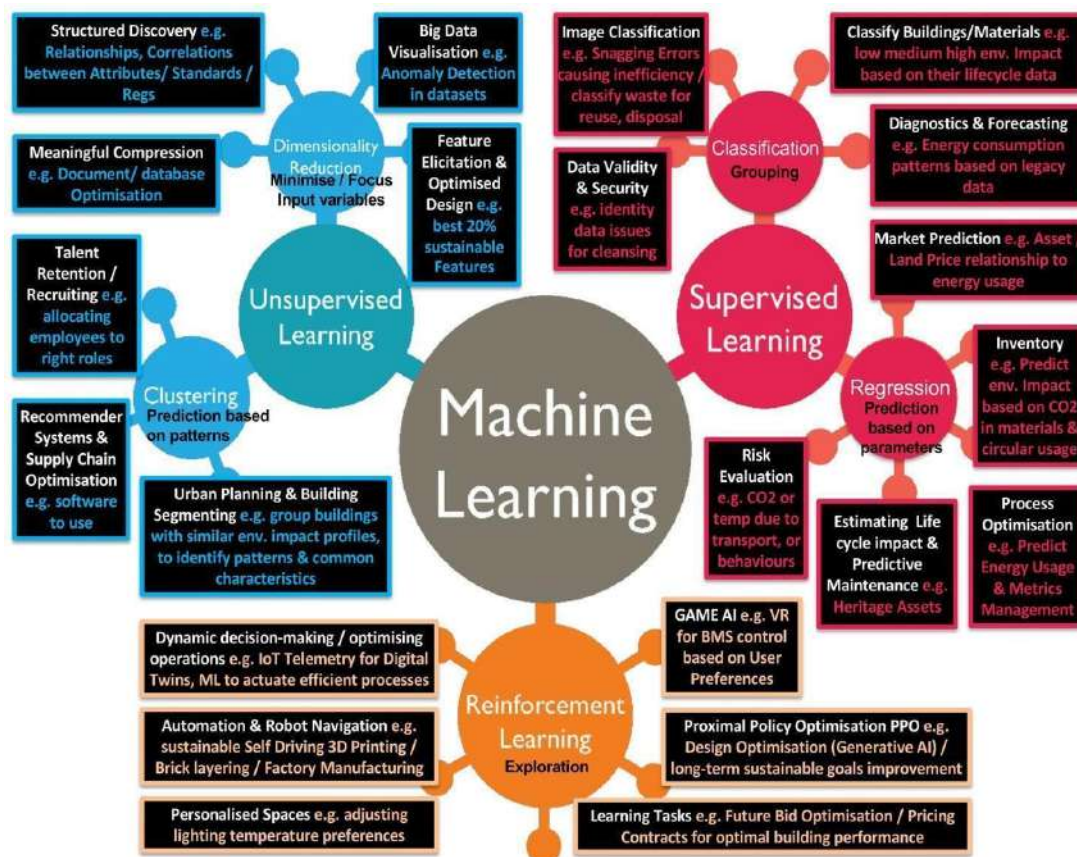


Figure 3: AI-Machine learning applications created within the project.

Alignment with all UN SDGs was as follows (Figure 4 and Figure 5):

- SDG_3: Health and well-being through improved indoor microclimates. Simulating natural ventilation, daylight distribution, thermal mass, and informing renovation strategies while preserving architectural integrity.
- SDG_7 and 13: Energy efficiency via predictive analytics for climate action, including HVAC system sizing, envelope performance (e.g., insulation/glazing/renewable energy integration). IES and OneClick LCA tools integrated with system assess embodied/operational carbon, with expected carbon savings of ~2.8 tonnes/year/building.
- SDG_9 and 11: Innovation and sustainable cities through smart heritage restoration. Simulated renovation workflows optimised time/cost for construction phasing, resource allocation, and budget forecasting.
- SDG_12: Circular economy via material reuse and lifecycle analysis
- SDG_4: Quality education via system integration in postgraduate curricula in the UK and Egypt. MSc BIM Management students (UK) participated in project data analysis, winning the Hong Kong Institute of BIM Award 2024.

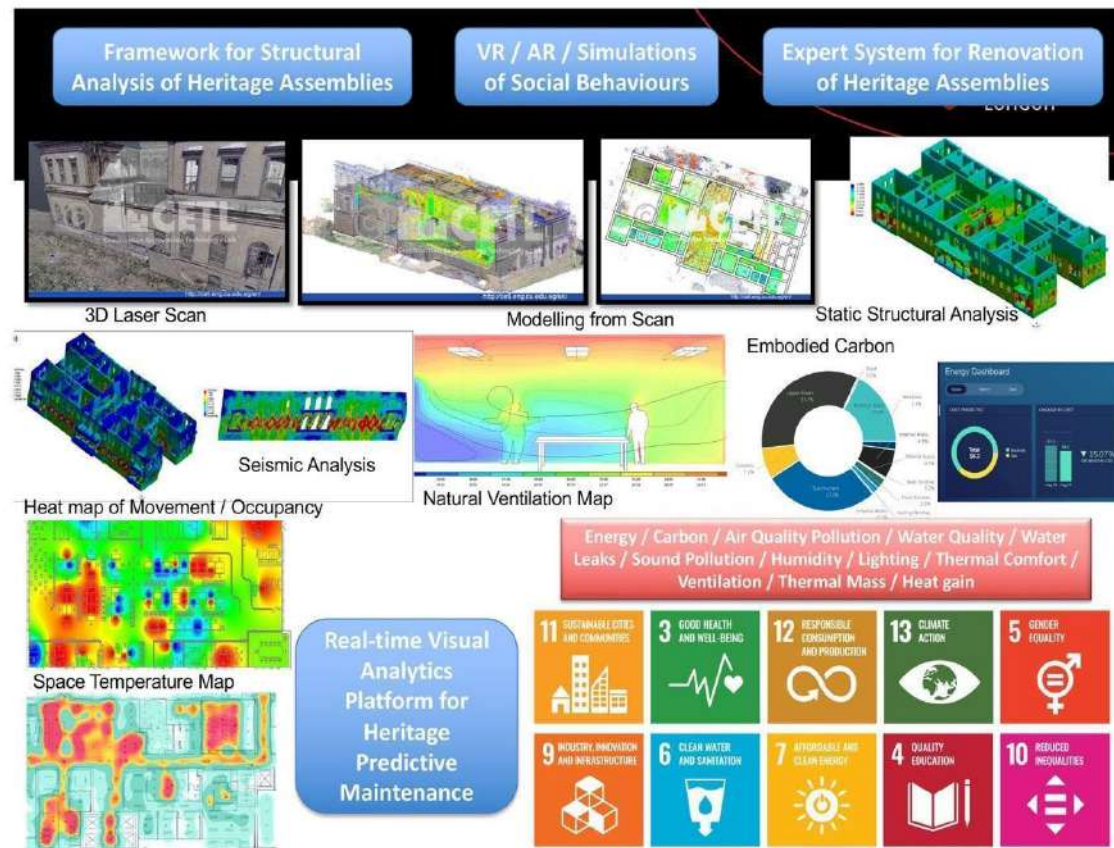


Figure 4: Project deliverables and their alignment to 10 SDGs (3,4,5,6,7,9,10,11,12,13).

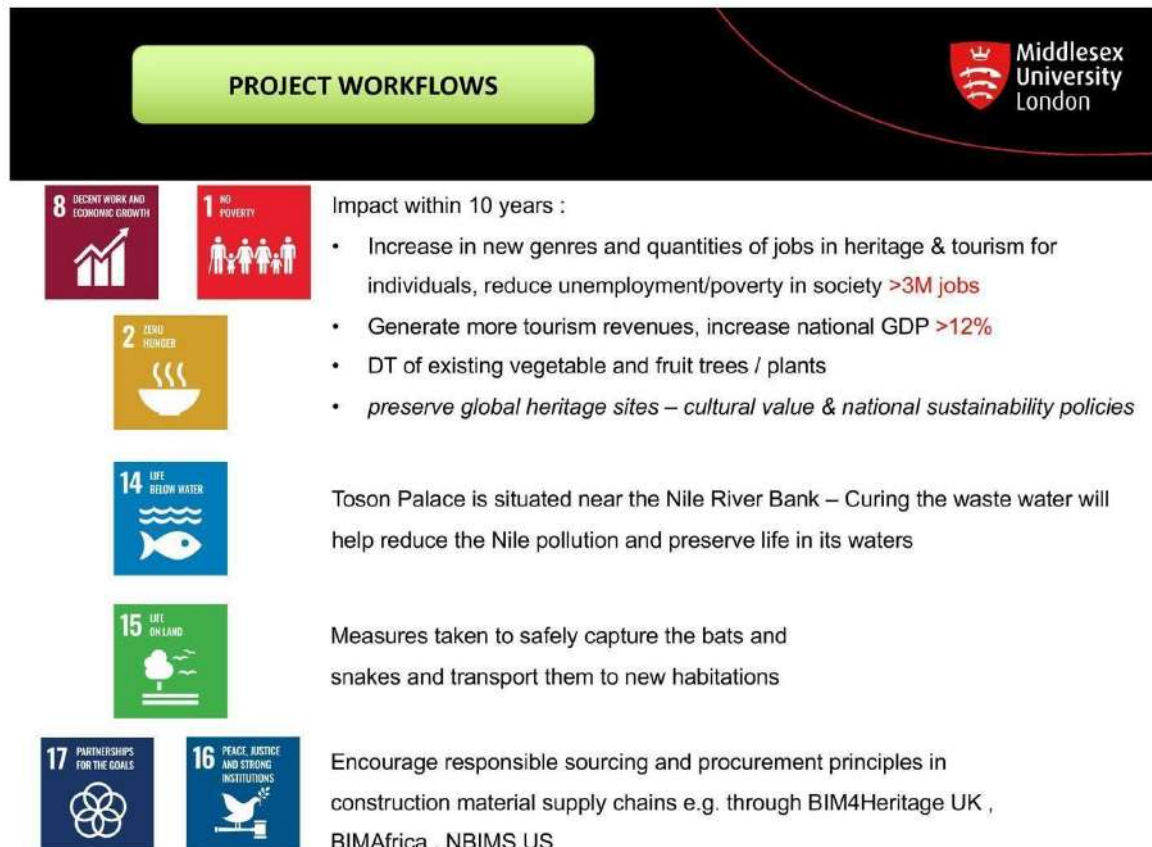


Figure 5: Project workflows and their alignment to 7 SDGs (1,2,8,14,15,16,17).

- SDG_15: Safe relocation of bats and snakes to protect biodiversity
- SDG_6 and 14: Drainage system upgrades to reduce pollution in the nearby Nile River, improving water quality and aquatic ecosystem protection.
- SDG_2: DT of fruit/vegetable farms on the estate to support food production
- SDG_1 and 8: Job creation in maintenance/IT/tourism, contributing to GDP growth ~£12 billion/year in tourism revenue and 3 million jobs over 5 years, reducing poverty and promoting work/economic growth.
- SDG_5 and 10: AI analysed spatial usage patterns, social simulations modelled different user groups' behaviour/interaction with heritage spaces, to improve accessibility, equality/inclusion, wayfinding, mobility, inclusive space planning, and cultural/community engagement.
- SDG_16 and 17: Governance and partnerships through policy engagement and international collaboration, for example, UK Parliament, BIM4Heritage, BIMAfrica, CIOB, Egyptian Ministry of Antiquities, adopting a new system to guide national heritage renovations adoption.

Conclusion

The FRESH-BIM/FRESH-DT projects represent innovation in integrating AI/DT technologies for built-environment sustainable transformation. By developing a scalable ecosystem spanning design/construction/operations, the projects demonstrated how intelligent systems address environmental/social/economic/governance challenges. Their alignment with all 17 UN SDGs, real-world implementation in heritage sites, and adoption by national/international stakeholders underscore global relevance. These projects offer a replicable model for construction and heritage conservation, setting a benchmark for interdisciplinary, data-driven sustainability.

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Part V
**Socio-Economic Empowerment and
Innovation**

Chapter 37

Tools2Thrive: A Scalable Tool Rental Model for Smallholder Farmers in Kenya

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Abstract

Subsistence farmers often struggle with productivity. The intervention of common hand tools significantly increases a farmer's resilience and is essential for tasks like soil preparation, planting, weeding, and harvesting, forming the foundation of many smallholder farming practices. While not nearly as good as mechanization, they are a first step to food security for many families. However, such tools remain out of reach for many farmers due to upfront costs. This paper details a year-long program to trial and scale a tool rental program through a community-based organization in western Kenya. Through a series of scaled experiments, we identified success characteristics for farmer renters, tool identification, rental agreements, data collection tools, organizational infrastructure, and field agent training and participation. We also identified several important failure points. Each of these elements were designed and trialled as part of a program called Tools2Thrive. Starting with \$110 and 20 tools, in just twelve months, the organization was able to grow itself from 549 farmer members to nearly 6000 members, 300 tools, eleven tool rental agents, and an organizational data collection tool that allows for real-time financial and impact tracking. The Tools2Thrive program and the software tool behind it will now be expanded into a second-year trial that involve nearly 20 community-based organizations, nearly 20,000 farmers, an expanded tool that will allow the organizations to track all the services they offer, and an expected revenue of nearly \$100,000 across the organizations.

Keywords: *Tool sharing, community-based organizations, smallholder farmers*

Introduction

Upfront costs to new and reliable hand tools limit the productivity and success of smallholder farmers. Local community-based organizations (CBOs) address community needs on a variety of issues, including gender, health, education, food security, clean water, and agriculture. With a large portion of the community practicing subsistence farming, agriculture programs provided by CBOs are vital to assisting farmers, helping them acquire inputs, tools, and knowledge of sustainable farming habits. Widespread demand for tools with limited structured access and/or rental systems remains a major

problem for CBOs to help their farmers. The idea of renting or hiring equipment to smallholder farmers is not a new idea, but sustainability has always been an issue^{1,2,3,4}.

In connecting with Kisumu West Aid (KIWA), a local community-based organization (CBO) in Kisumu, Kenya, we realized that smallholder subsistence farmers approach their local CBOs to address their needs and acquire resources, inputs, equipment, and training. Running their own agricultural initiatives, KIWA has served farmers in Kisumu West County and surrounding areas. In collaboration with KIWA, our team sought to better understand what makes CBO-led tool sharing programs successful and what are the key barriers to sustainability. The program run by KIWA was called Tools2Thrive.

Methods and Implementation

The trial program was run in two phases. Phase I from May 2024 to May 2025, Phase II started in June 2025 and is ongoing. This section of the paper will discuss the methods used to research this idea and then to track the program, as well as explain the implementation of Phase I with KIWA, and Phase II with eleven other organizations.

Data-Collection Methods

Data on farmer participation, rental practices, and revenue generation were collected through a combination of qualitative and quantitative methods. Structured interviews and focus group discussions captured farmer perspectives on tool accessibility, affordability, and challenges. Multiple question surveys were generated for both farmers and organizations to understand needs and impact. Organizational assessments measured CBO capacity, accountability systems, and integration of tool rentals into broader programming. Operational data on tool use, rental frequency, and income were tracked by CBOs using a range of record-keeping systems. These included informal memory-based tracking, paper-based ledgers, Excel spreadsheets, and, in select cases, KoboToolbox digital forms. This variation provided insights into both the adaptability of CBOs and the challenges of ensuring consistent, reliable data across diverse organizational contexts.

Phase I

Phase I of Tools2Thrive started with KIWA. In partnership with Penn State University (PSU), KIWA began a tool rental trial of hand-held jembes for the farmers in their community. Phase I of Tools2Thrive began testing the impact and sustainability of a CBO-run tool rental program. For a year,

¹Agrishare, Accessed on September 6, 2025 <https://www.agrishare.app>

²Kazibwe, Kenneth, "Innovators come up with Agrishare App to help solve farming challenges," *Nile Post* May 8, 2022, Accessed on September 6, 2025 <https://nilepost.co.ug/news/133361/innovators-come-up-with-agrishare-app-to-help-solve-farming-challenges>.

³Maschinenring, Accessed on September 6, 2025 <https://www.maschinenring.de/>.

⁴Schlick, Katharina, "Machinery Rings," Accessed on September 6, 2025 <https://entwicklungszusammenarbeit.maschinenring.de/kenia/en/>

the project tracked rentals, farmer income, CBO income, and farmer impact. Using a simplified and informal record-keeping system, KIWA and PSU monitored the growth of the program.

Phase II

Following a year of Tools2Thrive, several gaps in data collection for the CBOs and tool use prompted a reevaluation focusing on how to create a sustainable and repeatable model. Phase II of the project expanded to eleven other CBOs, including surrounding counties within a 200 km radius. These new organizations varied in size, number of farmers, and capacity but all had a want for a new program to address the agricultural needs of their community. Across the twelve organizations, approximately 70 CBO staff members were directly involved in the program, while over 300 farmers participated in focus group discussions and structured interviews conducted as part of program evaluation.

Results and Discussion

After collecting data to assess both the farmers' experience and the organizations' experiences in Phases I and II, we were able to discern some key learnings.

Key Learnings from Phase I

The initial pilot of Tools2Thrive with KIWA provided proof of concept and revealed several critical insights about farmer behavior, tool demand, and operational feasibility.

Farmer demand exists at scale. Even with a small starting inventory of ten tools, farmers were willing to participate and pay modest rental fees. Within six months, 549 members accessed tools, validating that affordability and accessibility were more significant barriers than willingness to pay.

High demand for basic hand tools. Low-value tools, especially *jembes*, *pangas*, and slashers, were consistently rented out. Starting with simple, affordable tools was an effective entry point for building trust and participation. It is an entry point for CBOs without the need of expensive machinery like tractors, ox-plows, or generators.

Need for structured record-keeping. KIWA initially relied on memory and paper-based tracking of tool rentals, which quickly became unsustainable and incorrect and led to misuse of the program. This underscored the importance of a basic and consistent formal tracking for accountability and growth.

Revenue generation potential. From the initial tool investment, KIWA was able to grow its inventory through the income generated. The model can be financially viable if scaled with structured reinvestment practices.

The first phase of the Tools2Thrive program not only expanded access to essential hand tools but also had a measurable impact on participating farmers' productivity and efficiency. A survey of 211 farmers revealed that prior to the program, tool ownership was low, averaging 1.7 tools per farmer, and most farmers relied on borrowing (70%) or sporadic purchases (12%) to meet their agricultural needs. Among those who rented in Phase I, the impact was significant: 75% reported increased productivity, 70% experienced a reduction in workload, and 60% observed an improvement in the quality of their

produce. Overall, 72% of all respondents indicated improved agricultural productivity, with an estimated average increase of 32%. Additionally, 78% of farmers reported a reduction in time and effort, saving on average four hours of labor per week. The demand for rental tools remains strong, with 85% of surveyed farmers expressing interest in renting more tools in the future.

The initial phase of the Tools2Thrive program began with a modest inventory of 10 jembes and served 487 farmer members. Over the course of the project, the initiative successfully reached an additional 5,743 farmers, bringing the cumulative total to 6,230 members. Of these, 3,812 farmers directly accessed and utilized the rented tools to support their agricultural activities. Through tool rental operations, the program generated a total revenue of Ksh. 245,000, the majority of which was reinvested to expand the tool inventory. This expansion grew the inventory from 10 jembes at inception to a total of 178 tools, comprising 133 jembes, 25 pangas, 10 mattocks, and 10 slashers. These achievements significantly enhanced smallholder farmers' capacity to cultivate their land more effectively, contributing to improved food security and strengthening household resilience in the target regions.

Key Learnings from Phase II

We had now realized that there was consistent demand for basic hand tools and growth potential for CBOs to not only help their communities but also generate income that could sustain projects. However, there was a question of was this replicable across different organizations (small vs large, semi-urban vs. rural, more-structured capacity vs. low capacity).

Variation in Record-Keeping Systems. CBOs adopted a wide range of tracking methods—from memory-based to paper ledgers, Excel spreadsheets, and KoboToolbox digital forms. This diversity highlighted both the adaptability of the model and the challenge of ensuring consistent, reliable data collection.

Role of Community Trust Systems. Local trust structures—including lead farmers, volunteers, and village administrators—proved essential in enforcing rental agreements and ensuring tool returns. These mechanisms extended the reach of CBOs but also raised questions about long-term reliability if leadership turnover occurs.

CBO Capacity as a Determinant of Success. Organizational maturity strongly influenced outcomes. Well-structured CBOs integrated existing rentals smoothly, while younger groups required significant support, particularly in financial management and accountability. Formal Memoranda of Understanding helped address this gap.

Financial Outcomes Highlight Both Promise and Risk. While KIWA did well, we do not know whether other CBOs will be able to generate enough income to reinvest into their program. A clear reinvestment framework is needed to ensure sustainable growth. The sustainability of this program is based on income generation by the CBOs. For KIWA, rental revenue (Ksh. 245,000) was primarily reinvested into tool acquisition (Ksh. 155,500), expanding tool capacity by 1,680%. Ksh. 10,000 was used on transportation and tool fixing. Remaining funds (Ksh. 89,500) supported office rent, utilities, and staff logistics, demonstrating early-stage operational reinvestment.

Conclusions

The Tools2Thrive trial has demonstrated that tool rental programs, when facilitated through trusted CBOs, can significantly increase access to essential hand tools, improve farmer productivity, and generate sustainable revenue streams for local organizations. Beginning with a modest inventory and limited financial investment, KIWA and the subsequent eleven partner CBOs proved that even basic tools meet impactful farmer demands. The trial highlighted both the successes (scaling membership, generating revenue, and expanding tool inventories) and the challenges (record-keeping, financial sustainability, and varying organizational capacity).

The broader impact of this trial shows that CBOs, when supported with structured systems and reinvestment strategies, can serve as effective intermediaries in bridging the gap between subsistence farmers and affordable, reliable agricultural tools. By empowering smallholder farmers with access to the tools they need, the model strengthens food security, supports household resilience, and creates pathways for CBOs to become financially independent and self-sustaining. With over 33 million smallholder farmers across sub-Saharan Africa, the replication potential is significant, offering a scalable solution to one of the region's most persistent agricultural challenges.

The next phase of Tools2Thrive will focus on key priorities including strengthening CBO financial management to ensure self-sufficiency, investing in capacity building to support organizations at different stages of development, and expanding the program to reach new communities. We will work with the twelve participating CBOs to implement a digital software platform that enables real-time tracking of rentals, revenues, and farmer impact and also support data-driven decision-making and scalability. Ultimately, the goal is to expand beyond western Kenya and establish Tools2Thrive as a replicable, community-centered model that equips millions of smallholder farmers across Africa with the tools they need to thrive.

Acknowledgements

The authors would like to acknowledge the leadership, innovation, and vision of Joshua Oliech and the program team at KIWA without whom Tools2Thrive would never have happened. The CBOs and their leaders who were part of Phase II all took a big risk to join this program, and we thank them for this. The team at Penn State HESE who worked on this project from the early stages and the program leadership there.

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Chapter 38

The Second Act of Life: Unveiling Podcast Narratives of Purpose and Reinvention Among Midlife Entrepreneurs

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Abstract

This study investigates the emerging phenomenon of midlife entrepreneurship, defined as entrepreneurial activity initiated by individuals aged 45 and older. While prior research has largely centred on younger founders, the distinct trajectories, motivations, and constraints of midlife entrepreneurs remain underexplored. To address this gap, the study analyses 34 U.S.-based podcast episodes discussing midlife entrepreneurship, with a focus on identifying the availability of business training in this format. Findings reveal that, rather than offering structured technical training, most episodes emphasise narratives of career reinvention, identity negotiation, and family transitions. For a demographic with substantial professional experience, the process of self-redefinition emerges as a critical component of entrepreneurial transition, often outweighing the need for basic business skills. These insights challenge age-related stereotypes and reposition midlife individuals as a dynamic and adaptive force within the entrepreneurial landscape.

Keywords: *Midlife entrepreneurs, Identity, Purpose, Pivoting*

Introduction

Midlife entrepreneurship is emerging as a powerful yet underexplored force within the innovation economy. Contrary to the enduring myth that entrepreneurial success is the domain of the young, recent evidence reveals that individuals in their 50s launch businesses at rates comparable to those in their 20s, and often with equal or greater success¹. Older founders (~50 years and above) are more likely to introduce new products/services to the market than younger founders². The average startup founder is typically in their early to mid-40s, especially in tech and high-growth companies³. Since 2016, those aged 45 to 54 have consistently demonstrated the highest levels of entrepreneurial activity⁴, positioning midlife as a critical period for entrepreneurial reinvention.

¹Britt, Robert Roy, "How Do Older Entrepreneurs Compare to Younger Business Owners?" *Uschamber.com*, CO- by U.S. Chamber of Commerce, August 7, 2025 <https://www.uschamber.com/co/grow/thrive/middle-aged-entrepreneurs-success>

²Murmann, et al., "How Does Late-Career Entrepreneurship Relate to Innovation?" *Research Policy*, 52, no. 6 (2023): 104763.

³Somers, Meredith, "The 20-Year-Old Entrepreneur Is a Lie," *MIT Sloan*, April 20, 2018 <https://mitsloan.mit.edu/ideas-made-to-matter/20-year-old-entrepreneur-a-lie>.

⁴Kauffman Foundation, *Kauffman Indicators of Entrepreneurship*, 2025 <https://indicators.kauffman.org/indicator/rate-of-new-entrepreneurs/2020>.

This demographic, however, navigates a uniquely complex life stage. Midlife adults, both men and women, are typically seasoned professionals balancing demanding careers with family responsibilities, often as part of the so-called “sandwich generation” caring simultaneously for children and ageing parents⁵. They report heightened financial pressures, decision fatigue, and lower life satisfaction compared to younger and older cohorts^{6, 7}, even as demographic shifts and hormonal changes further shape their experiences⁸. While only a minority experience a stereotypical “midlife crisis,” this period frequently prompts deep self-reflection and a desire for meaningful change⁹.

Against this backdrop, entrepreneurship increasingly represents a pathway to autonomy, purpose, and personal fulfilment^{10, 11}. Yet critical questions remain unanswered: How do midlife entrepreneurs reconcile the invisible load of work–family conflict with the demands of business ownership? Does entrepreneurship enhance well-being and life satisfaction? And, given their extensive experience, what forms of training and support best enable them to translate entrepreneurial intentions into action?

Despite their growing presence, midlife entrepreneurs remain largely overlooked in mainstream research^{12, 13}. Understanding their learning needs is essential for designing effective interventions that support successful transitions into entrepreneurship. To address this gap, this study investigates an emerging and accessible learning medium, podcasts. Specifically, it explores the following research question: What business training is available in podcast episode format?

⁵Been, Laura E, et al., “Hormones and neuroplasticity: A lifetime of adaptive responses,” *Neuroscience and Biobehavioral Reviews*, 132 (2022): 679–90.

⁶Almeida, David, and Melanie C. Horn, “Is Daily Life More Stressful during Middle Adulthood,” *How Healthy Are We?: A National Study of Well-Being at Midlife*, 687, (2004): 425–51 <https://doi.org/10.1037/e316982004-001>.

⁷Blanchflower, David G, and Carol L Graham, “The U Shape of Happiness: A Response,” *Perspectives on Psychological Science: A Journal of the Association for Psychological Science*, 16, no. 6 (November 2021): 1435–46 <https://doi.org/10.1177/17456916209843>

⁸Oliveira, Rui F, “Social behavior in context: Hormonal modulation of behavioral plasticity and social competence,” *Integrative and Comparative Biology*, 49, no. 4 (October 2009): 423–40. <https://doi.org/10.1093/icb/icp055>.

⁹Lachman, Margie E, et al., “Midlife as a Pivotal Period in the Life Course: Balancing Growth and Decline at the Crossroads of Youth and Old Age,” *International Journal of Behavioral Development*, 39, no. 1 (2015): 20–31, DOI: 10.1177/0165025414533223.

¹⁰Backman, Mikaela, and Charlie Karlsson, “Who says life is over after 55? Entrepreneurship and an aging population”, CESIS Electronic Working Paper Series, 325, (2013): 31. <https://static.sys.kth.se/itm/wp/cesis/cesiswp325.pdf>

¹¹Halvorsen, Cal J, and Yu-Chih Chen, “The diversity of interest in later-life entrepreneurship: Results from a nationally representative survey of Americans aged 50 to 70,” *PLoS One*, 14, no. 6 (2019): e0217971, DOI: 10.1371/journal.pone.0217971.

¹²Halvorsen, Cal J, and Yu-Chih Chen, “The diversity of interest in later-life entrepreneurship: Results from a nationally representative survey of Americans aged 50 to 70, (2019): e0217971.

¹³Viljamaa, Anmari, et al., “Part-Time Entrepreneurship in the Third Age: Well-Being and Motives,” *Small Enterprise Research*, 29, no. 1 (2022): 20–35. DOI: 10.1080/13215906.2021.2000483

Methodology

Data Collection

The dataset comprised 34 U.S.-based podcast episodes, from 29 distinct podcasts/channels, amounting to approximately 22 hours of audio content (please see the playlist here: [MIDLIFE ENT](#)). All episodes were sourced from YouTube Audio on 8th September 2025, and were selected using the keyword “midlife entrepreneur”. The podcast format was chosen due to its growing role as an accessible and flexible medium for entrepreneurial learning.

Table 1: Characteristics of the sample.

Host	Frequency	Format	Frequency
Male host	6	Monologue	6
Female host	24	Interview to female guest	23
Tandem host	4	Interview to male guest	5
Total	34		34

Inclusion and Exclusion Criteria

Episodes were included if they explicitly addressed the entrepreneurial experiences of individuals in midlife. Content primarily offering parenting advice or relationship counselling was excluded. However, episodes discussing the impact of relationships and significant family events, such as child-rearing, divorce, or bereavement, on the entrepreneurial journey were retained, given their relevance to understanding midlife transitions.

Data Analysis

A thematic analysis¹⁴ approach was employed to identify recurring patterns and themes within the narratives. The analysis followed an iterative process: 1) getting familiar with the data, 2) generating initial codes, 3) searching for themes, 4) reviewing themes with constant comparison, whereby emerging codes and categories were continuously refined against new data, 5) defining and naming themes, and finally 6) producing the report. This method enabled the identification of both commonalities and variations in how midlife entrepreneurs articulate their motivations, challenges, and strategies.

Ethical Considerations

When analysing public data from YouTube Audio, it is essential to consider the ethical principles. Researchers must respect the privacy and autonomy of content creators, even when material is publicly accessible. Care should be taken to avoid misrepresentation or decontextualisation of creators’

¹⁴Braun, Virginia, and Victoria Clarke, “Using Thematic Analysis in Psychology,” *Qualitative Research in Psychology*, 3, no. 2 (2006): 77–101.

<https://www2.uwe.ac.uk/services/Marketing/students/Newstudents/HAS/Using%20thematic%20analysis%20in%20psychology.pdf>

narratives, and to acknowledge the original sources appropriately. Furthermore, analysis should be carried out transparently, with sensitivity to the potential impact findings may have on individuals and communities. These measures help ensure that the research upholds integrity while responsibly engaging with publicly available digital content.

Results

Figure 1 illustrates the interconnected dimensions shaping the midlife entrepreneurial experience, with a particular emphasis on the business dimension. The diagram comprises four overlapping spheres: Well-being, relationships, business, and money, all converging around a central construct of “Meaning”.

This interconnectedness underscores the complexity of entrepreneurial reinvention in midlife, where business aspirations are deeply entangled with personal, relational, and financial considerations.

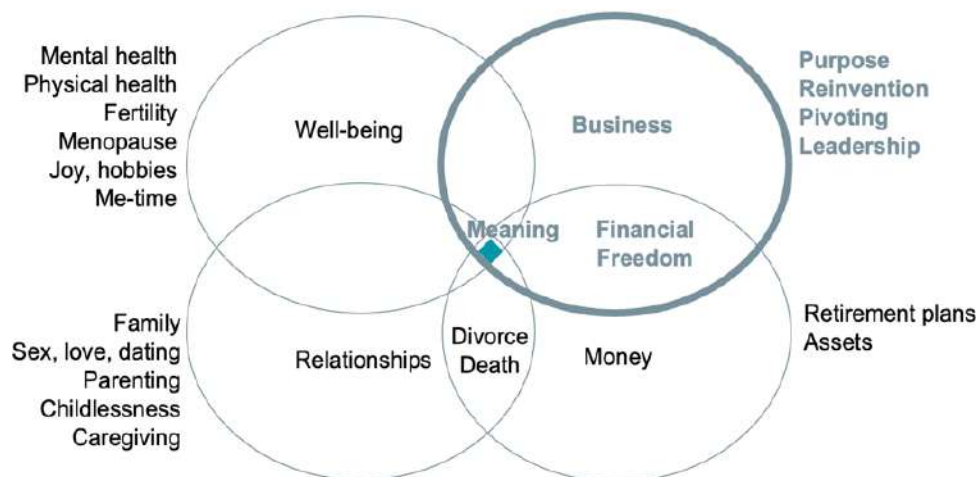


Figure 1: Emerging themes for midlife entrepreneurial experience.

This study focuses on the business dimension. Within the business sphere, key themes include 1) purpose, alongside 2) reinvention, 3) pivoting, 4) leadership, and 5) financial freedom, reflecting the transformative nature of midlife entrepreneurship.

1. Purpose helps create a brand

The 'second act', often mentioned in social media, refers to the phase in midlife when individuals reconsider their goals and aspirations, often leading to a renewed sense of purpose. Building a personal brand around this purpose involves identifying how one's unique experiences can positively impact society. For instance, someone who spent years in corporate management might reassess their priorities in midlife and choose to start a nonprofit organization. In this example, their brand then becomes associated with social impact and leadership in the nonprofit sector.

2. Reinvention of Identity

For midlife individuals, the transition to entrepreneurship often entails profound identity work. After decades of professional experience, many have internalised roles and values tied to organisational careers, making the shift to self-employment a challenge to their sense of self. This reinvention process requires not only acquiring new business skills but also renegotiating personal and professional

identities—moving from being a specialist or corporate leader to embracing the uncertainty and autonomy of entrepreneurial life. Such transitions are compounded by structural and psychological barriers: fear of financial instability, age-related stereotypes, and the pressure of sustaining family responsibilities. Moreover, midlife entrepreneurs frequently grapple with the tension between continuity and change—seeking to leverage accumulated expertise while redefining purpose and meaning in ways that align with evolving life priorities. These dynamics underscore that entrepreneurship at midlife is not merely an economic decision but a deeply transformative process of self-concept reconstruction.

3. Pivoting the Business Model

For midlife entrepreneurs, pivoting represents both a strategic and deeply personal recalibration of their business trajectory. Unlike early-stage founders, these individuals often operate within established ventures, making decisions to downsize, scale, or alter business models in response to shifting markets, technological disruptions, or evolving personal priorities. Such pivots are rarely driven by growth ambitions alone; they frequently reflect a desire to align business operations with lifestyle goals, health considerations, or caregiving responsibilities. This process can involve difficult trade-offs, such as reducing team size to regain autonomy, transitioning from product-based to service-oriented models, or embracing digital platforms to maintain flexibility. While pivoting offers opportunities for renewal and sustainability, it also challenges midlife entrepreneurs to renegotiate their sense of competence and identity, as prior markers of success may no longer apply. Ultimately, these strategic shifts underscore the dynamic interplay between external pressures and internal aspirations in sustaining entrepreneurial engagement during midlife.

4. Leadership that Serves Others

Leadership in midlife entrepreneurship often reflects a shift from traditional hierarchical models towards more conscious and value-driven approaches. Having decades of professional experience accumulated, many midlife founders prioritise optimism, empathy, and purpose as core leadership qualities, seeking to create businesses that align with personal values and social impact goals. Unlike early-career entrepreneurs, they frequently emphasise team empowerment and collaborative decision-making, drawing on their managerial expertise while adapting to the agility required in entrepreneurial contexts. This stage of life also fosters a heightened sense of self-awareness, prompting leaders to adopt practices that support well-being—both their own and that of their teams. Conscious leadership, therefore, becomes a strategic asset, enabling midlife entrepreneurs to navigate uncertainty with resilience while cultivating trust and loyalty within their organisations. Ultimately, leadership at midlife is less about authority and more about authenticity, adaptability, and purpose-driven influence.

5. Financial Freedom Amidst Life Disruptions

For many midlife individuals, the pursuit of entrepreneurship is closely tied to aspirations for financial freedom, particularly following major life disruptions such as divorce or the death of a loved one. These events often act as catalysts for reassessing financial security and long-term independence. Divorce, for instance, can significantly alter household income and retirement plans, creating both urgency and motivation to establish new revenue streams. Similarly, bereavement may prompt individuals to reflect

on the fragility of life and prioritise autonomy over traditional employment structures. In this context, entrepreneurship is frequently perceived not only as a means of generating income but as a pathway to regain control, rebuild stability, and create a legacy. However, these expectations can heighten the psychological and financial risks of business ownership, as individuals balance the desire for freedom with the realities of start-up uncertainty and resource constraints.

Conclusions

This study not only challenges age-related stereotypes but also repositions midlife individuals as a dynamic, underutilised force in the entrepreneurial landscape, essential to driving innovation, fostering inclusive growth, and building more resilient economies in an ageing world.

Acknowledgement

The author gratefully acknowledges the support of the Dubai Foundation, which enabled attendance of Professor's Programme at *Prototypes for Humanity 2025*. An earlier version of this manuscript was presented and discussed at this event, and the feedback received there contributed meaningfully to its development.

Declaration

The authors declare that artificial intelligence tools were used in the preparation of this manuscript. The use of these tools was limited to assisting with grammar and language, and all outputs were carefully reviewed, verified, and edited by the authors to ensure accuracy, originality, and alignment with academic standards. The authors take full responsibility for the content of this manuscript, including any sections that were supported by AI tools. No AI system was used to generate original research findings, interpret results independently, or draw conclusions without human intervention.

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Chapter 39

Eco-efficient Valorisation of Spent Yeast: Protein and β -Glucan Fractions Recovery for Health-promoting Applications

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Abstract

The valorisation of agro-industrial waste is vital to advanced sustainable innovation in the pharmaceutical and nutraceutical sectors. This study offers a novel eco-conscious approach for transforming spent yeast (microorganism used in fermentation), an abundant underutilised residue of food and beverage industries, into high-value functional ingredients. Rich in β -glucans, proteins, and polyphenols, with antioxidant, anti-inflammatory, and anti-cancer properties, spent yeast holds great potential as a natural resource. Using instant controlled pressure drop, known as “Détente Instantanée Contrôlée” (DIC), together with ultrasound or other cell-breaking methods improved bioactive compound extraction by 40–45% and reduced energy use up to 20% compared with traditional techniques. The extracted bioactives will be subsequently encapsulated in nanoparticles to enhance their stability, bioavailability, and targeted delivery. Furthermore, to personalise applications more effectively, artificial intelligence will be integrated to optimise formulations in real time, tailored to individual health profiles and functional goals. This innovative framework is multidisciplinary, cost-effective, energy-efficient, and scalable, aligning with circular economy principles and supporting the sustainable upcycling of industrial waste.

In conclusion, the adopted approach not only reduces environmental impact but also opens new avenues for clean-label, science-backed nutraceutical development. This work demonstrates how green processing technologies, supported by digital innovation, can transform waste into strategic health-promoting products, bridging biotechnology, AI, and sustainability for the future of functional nutrition.

Keywords: *Spent yeast, Green processing, Nanoencapsulation, Sustainability, Circular economy*

Introduction

The rapidly growing global population is driving higher demand for food and commodities, with projections indicating a 50-60% increase in total global food demand between 2019 and 2050¹, resulting

¹Falcon, Walter P. et al., “Rethinking Global Food Demand for 2050,” *Population and Development Review*, 48, no. 4 (2022): 921–57 <https://doi.org/10.1111/padr.12508>.

in the generation of massive agricultural and food waste². Extensive agriculture produces large volumes of crop residues that often remain underutilised, creating environmental and economic challenges. To address these concerns, efficient management and biotechnological valorisation of agro-food wastes have become essential strategies for resource optimisation and sustainability³. Among these residues, spent yeast represents an abundant yet underexploited by-product, produced not only in baking but also in vinegar fermentations, bioethanol, and other biotechnological processes⁴. Spent yeast has a high chemical oxygen demand (COD) of 0.53 kg/hL and cannot be released into wastewater streams without prior treatment, as doing so would cause severe environmental harm. Traditionally considered waste, spent yeast is now increasingly recognised as a rich source of functional biomolecules, including β -glucans (50–60%), proteins (45–60%), polyphenols (3–5%), and antioxidants, all known for their immunomodulatory, antioxidant, anti-inflammatory, and anticancer activities. These attributes make it an attractive candidate for the development of functional ingredients and natural health products⁵.

Recent advances in green extraction technologies have opened new pathways for efficiently and sustainably recovering bioactive compounds from yeast biomass. In particular, Instant Controlled Pressure Drop (DIC), a thermo-mechanical pre-treatment, combined with ultrasonication or other cell-disruption methods, has demonstrated the ability to enhance mass transfer, improve extraction yields, and reduce processing time and energy consumption⁶. Such innovations not only improve the release of intracellular components but also preserve the structural integrity and functionality of sensitive molecules. Beyond extraction, nanoencapsulation strategies have emerged as powerful tools to increase the stability, bioavailability, and targeted delivery of yeast-derived compounds, enabling their incorporation into a wide range of nutraceutical, pharmaceutical, cosmetic, and functional food applications.

In this context, this study aims to demonstrate an integrated strategy for upcycling spent yeast into functional raw materials, showcasing how advanced extraction and encapsulation can synergistically induce innovation in the nutraceutical sector. By leveraging these approaches, the work contributes to waste reduction, resource efficiency, and sustainability targets, while delivering next-generation sustainable health-promoting products.

²Ezeorba, Timothy Prince Chidike et al., “Recent Advances in Biotechnological Valorization of Agro-Food Wastes (AFW): Optimizing Integrated Approaches for Sustainable Biorefinery and Circular Bioeconomy,” *Bioresource Technology Reports*, 26 (2024): 101823 <https://doi.org/10.1016/j.biteb.2024.101823>.

³Klai Nouha et al., “18 - Agro-Industrial Waste Valorization for Biopolymer Production and Life-Cycle Assessment Toward Circular Bioeconomy.” In *Biomass, Biofuels, Biochemicals*, edited by Ashok Pandey, Rajeshwar Dayal Tyagi, and Sunita Varjani, *Elsevier*, (2021) <https://doi.org/10.1016/B978-0-12-821878-5.00007-6>.

⁴Luzón-Quintana Luz María et al., “Biotechnological Processes in Fruit Vinegar Production,” *Foods*, 10 no. 5 (2021): 945 <https://doi.org/10.3390/foods10050945>.

⁵Jaeger Alice et al., “Brewer’s Spent Yeast (BSY), an Underutilized Brewing By-Product,” *Fermentation*, 6, no. 4 (2020): 4 <https://doi.org/10.3390/fermentation6040123>.

⁶Nader Joelle et al., “Instant Controlled Pressure Drop (DIC) as an Emerging Food Processing Technology,” In Gavahian, M. (eds) *Emerging Food Processing Technologies. Methods and Protocols in Food Science*, (Humana, New York, NY, 2022) https://doi.org/10.1007/978-1-0716-2136-3_16.

Results and Discussion

1. Multi-step Biomass Fractionation of Spent Yeast Waste: Chemical and Biological Characterisation

The recovery of high-value compounds from spent yeast was achieved through a multi-step fractionation strategy (Figure 1). After initial washing and optional de-bittering to remove aromas and nucleic acids, cell disruption was performed using sonication for 30 min with an ultrasonic processor probe UP100H at 30 kHz (Hielscher, Germany), facilitating the breakdown of the cell wall and release of bound biomolecules. Alkaline extraction in NaOH effectively solubilised the cell wall proteins, while subsequent isoelectric precipitation of the supernatant promoted their selective recovery in purified form. In parallel, the insoluble pellets generated during this process contained structural polysaccharides, primarily β -glucans, allowing a natural separation of protein and β -glucan-rich fractions. The compositional and functional characterisation of the recovered fractions highlights the efficiency of the multi-step extraction strategy (Table 1). The protein isolates (PH: non-debittered and PG: debittered) exhibited very high protein purity (70.9% and 66.4%, respectively) and retained significant amounts of polyphenols (28.5–24.9 mg GAE/g DM), contributing to their moderate antioxidant activities. In contrast, the β -glucan concentrates (BA: debittered and BB: non-debittered) showed high purity in β -glucans (77.8% and 62.7%), with minimal protein contamination (< 5%) and high radical-scavenging activities (DPPH: 76.9–72.6 mg TE/g DM; ABTS: 97.6–89.4 mg TE/g DM), despite their low polyphenol content. These results suggest that antioxidant properties in β -glucan fractions originate not only from residual phenolics but also from structural features of β -glucans and their synergistic interactions. Overall, this integrated approach effectively separates the spent yeast into two nutritionally and functionally valuable fractions, proteins and β -glucans, ensuring a near-zero-waste process with minimal losses, thus reinforcing its potential for sustainable valorisation in nutraceutical and functional food applications.

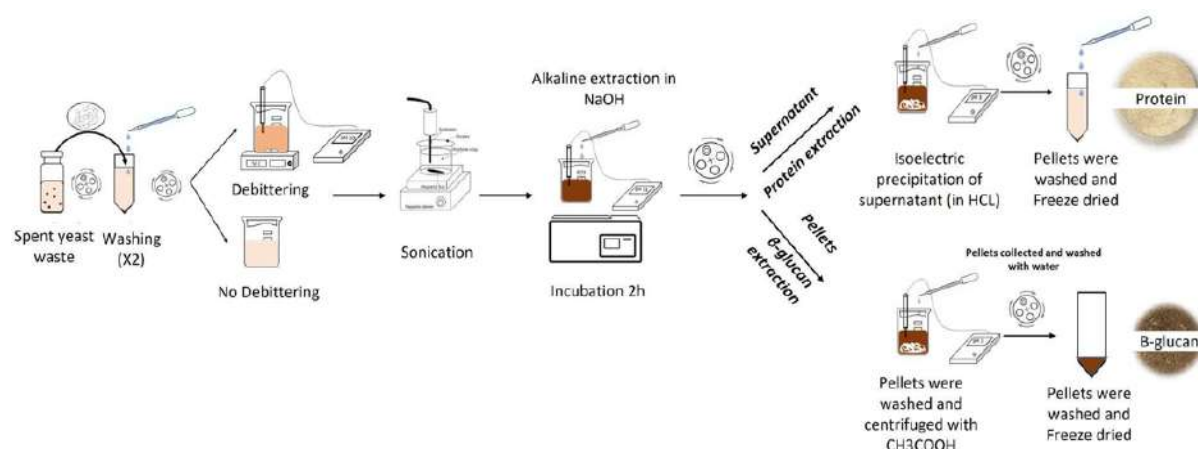
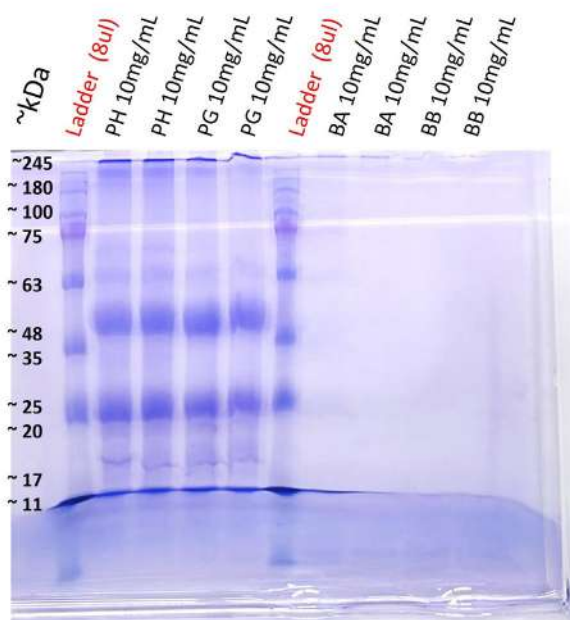


Figure 1: Schematic representation of the multi-step biomass fractionation of spent yeast waste into proteins and β -glucans.

Table 1: Chemical and biological composition of Protein and β -glucan-rich extract represented by (mean $\pm$ SD).

	Protein extract		β -glucan extract	
	PH	PG	BA	BB
Dry matter (%)	95.6 $\pm$ 1	95.7 $\pm$ 1.2	94.5 $\pm$ 1.5	94.8 $\pm$ 1.1
Ash content (%)	8.0 $\pm$ 0.5	6.2 $\pm$ 1.5	5.9 $\pm$ 1	5.2 $\pm$ 1.2
Protein content (%)	70.9 $\pm$ 4.6	66.4 $\pm$ 4.61	5 $\pm$ 1.2	3.5 $\pm$ 2.1
β -glucan content (%)	<1	<1	77.8 $\pm$ 2.6	62.7 $\pm$ 1.5
TPC (mg GAE/g DM)	28.5 $\pm$ 0.6	24.9 $\pm$ 0.4	12.2 $\pm$ 0.1	12.8 $\pm$ 0.3
DPPH (mg TE/g DM)	19.9 $\pm$ 1.1	9.8 $\pm$ 2.0	76.9 $\pm$ 1.6	72.6 $\pm$ 7.4
ABTS (mg TE/g DM)	33.5 $\pm$ 1.6	30.3 $\pm$ 1.6	97.6 $\pm$ 3.5	89.4 $\pm$ 3.7

SDS–PAGE analysis revealed distinct peptide bands for the protein extracts, while the β -glucan fractions showed non-detectable protein cross-contamination (Figure 2). The protein extracts displayed multiple peptide bands between 15 and 100 kDa. In the High MW region, a light band at $\sim$ 180 kDa was seen corresponding to large protein aggregates. Faint bands at $\sim$ 75 and $\sim$ 63 kDa reflected less abundant high-molecular-weight peptides. Sharp bands in the 35–48 kDa region are typical of structural and enzymatic proteins, whereas bands in the 20–25 kDa range indicate the presence of smaller peptides or partially degraded proteins. In contrast, no protein bands were detected in the β -glucan extracts, confirming the efficiency of the extraction process in eliminating protein residues.

**Figure 2:** SDS-PAGE gel of the protein-rich extracts (10 mg/mL of PH and PG) and β -glucan-rich extracts (10 mg/mL of BA and BB) recovered from spent yeast.

Moreover, mineral analysis using the XRF technique revealed a balanced composition, with high levels of essential macronutrients such as sulphur, potassium, and calcium, along with trace elements like

iron, manganese, and copper (Table 2). Importantly, no toxic heavy metals were observed, confirming the safety and nutritional quality of both extracts.

Table 2: Mineral content (mean $\pm$ SD) of the protein-rich extracts (10 mg/mL of PH and PG) and β -glucan-rich extracts (10 mg/mL of BA and BB) recovered from spent yeast.

Mineral	Protein extract		β -glucan extract	
	PH (ppm $\pm$ SD)	PG (ppm $\pm$ SD)	BA (ppm $\pm$ SD)	BB (ppm $\pm$ SD)
S	4402.0 $\pm$ 73.2	3840.3 $\pm$ 243.5	707.0 $\pm$ 48.5	512.7 $\pm$ 40.0
Ca	360.0 $\pm$ 43.6	757.0 $\pm$ 25.5	1417.3 $\pm$ 194.4	1270.3 $\pm$ 175.5
Fe	175.7 $\pm$ 4.5	68.7 $\pm$ 15.6	471.0 $\pm$ 5.0	471.7 $\pm$ 36.4
K	2388.3 $\pm$ 59.7	865.7 $\pm$ 25.5	76.3 $\pm$ 1.2	77.0 $\pm$ 0.8
Mn	34.7 $\pm$ 1.7	33.3 $\pm$ 0.9	33.3 $\pm$ 0.5	32.3 $\pm$ 0.5
Cu	14.0 $\pm$ 0.0	14.3 $\pm$ 0.2	18.0 $\pm$ 4.1	24.0 $\pm$ 2.2
Zn	36.0 $\pm$ 2.4	77.0 $\pm$ 3.7	13.0 $\pm$ 0.8	14.0 $\pm$ 3.6
Mo	13.0 $\pm$ 0.8	11.3 $\pm$ 0.5	9.3 $\pm$ 1.2	9.0 $\pm$ 0.8
Hg	< LOD	< LOD	< LOD	< LOD
Pb	< LOD	< LOD	< LOD	< LOD
Au	< LOD	< LOD	< LOD	< LOD

In contrast to HPH and other intensive techniques, which frequently induce protein degradation and compositional alterations⁷, this process ensured greater preservation of both proteins and minerals. These results highlight that the applied protocols successfully generated protein-rich fractions alongside highly purified β -glucan preparations, both of which are suitable for applications in food and nutraceutical formulations.

2. Thermal Stability of Protein and β -glucan-rich Extracts

Thermogravimetric analysis (TGA) assesses thermal stability and indirectly indicates the potential shelf life of the extracted protein and β -glucan fractions from spent yeast (Figure 3). Both protein fractions exhibited a typical three-step degradation pattern, starting with moisture loss below 120°C, followed by a gradual weight reduction up to ~250°C over 20 min, and a major degradation phase between 280 and 330°C after 30 min. The debittered protein extract (PG) exhibited delayed thermal decomposition and a higher final ash yield compared to PH, indicating that debittering enhanced structural integrity by removing low-molecular-weight impurities and bitter compounds that would otherwise catalyze breakdown.

A similar trend was observed for the β -glucan fractions. The debittered sample (BA) degraded at slightly higher temperatures and showed higher residue compared to the non-debittered counterpart (BB), reflecting improved resistance to thermal cleavage of the polysaccharide chains, consistent with the

⁷Lee Suyoon et al., "Characterization of Yeast Protein Isolates Extracted via High-Pressure Homogenization and pH Shift: A Promising Protein Source Enriched with Essential Amino Acids and Branched-Chain Amino Acids," *Journal of Food Science* 89 no. 2 (2024): 900–912 <https://doi.org/10.1111/1750-3841.16918>.

findings of Bai et al⁸. Overall, both extracts demonstrated superior thermal stability and extended shelf life. These findings demonstrate that this multistep fractionation process not only enhances purity but also strengthens the thermal stability and shelf life of spent yeast-derived ingredients, which favours their suitability for use in food and nutraceutical applications requiring heat processing and long-term storage.

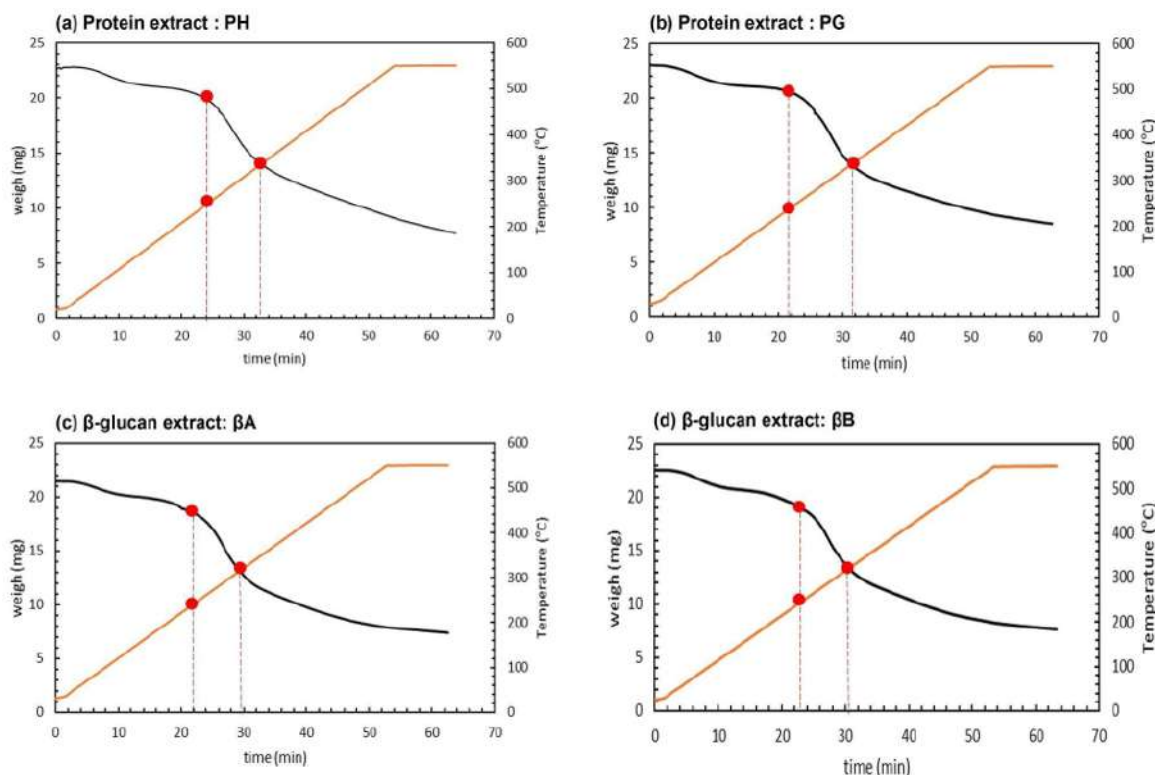


Figure 3: Thermogravimetric analysis (TGA) curves of protein extract (a) and (b), and β -glucan extract (c) and (d). Samples were heated from 30 to 550°C for 60 min (10°C/ per min).

3. Sustainability Indicators

The sustainability parameters represented by process mass intensity (PMI), energy score intensity (ESI), and water intensity (WI) provide a comprehensive assessment of the environmental footprint of the extraction processes (Table 3). The non-debittered protein extract (PH) showed the most favourable profile, with the lowest values across all three indices (PMI = 23.33, ESI = 852, WI = 143), indicating minimal consumption of raw materials, energy, and water. In contrast, the debittered protein fraction (PG) required slightly higher inputs, particularly in water, likely due to additional washing steps after debittering. β -glucan extractions were more resource-intensive overall, with the debittered β -glucan showing the highest energy and water demands compared to the non-debittered β -glucan fraction. These findings demonstrate that protein recovery, especially the non-debittered form, is considerably more sustainable than β -glucan isolation, underlining the relative efficiency of protein extraction

⁸Bai, Yi-Peng, Hui-Ming Zhou, Ke-Rui Zhu, and Qin Li. 2021. "Effect of Thermal Processing on the Molecular, Structural, and Antioxidant Characteristics of Highland Barley β -Glucan." *Carbohydrate Polymers*, 271, (November): 118416 <https://doi.org/10.1016/j.carbpol.2021.118416>.

processes. When compared with previously reported sustainable metrics for protein-rich extract from spent yeast using sonication (PMI=919-1904, WI=909-1882, and ESI=1137-2353), our results show a markedly improved balance between mass, energy, and water efficiency⁹. These findings suggest that this integrated process preserves proteins and β -glucans with reduced environmental costs, offering a more sustainable alternative for yeast biomass valorisation in the food and nutraceutical sectors.

Table 3: Sustainability parameters (PMI, ESI, and WI) for the extraction processes of protein and β -glucan fractions.

	Protein extract		β -glucan extract	
	PH (mean $\pm$ SD)	PG (mean $\pm$ SD)	BA (mean $\pm$ SD)	BB (mean $\pm$ SD)
PMI	23.33	29.75	29.0	23.0
ESI	852	1359	1989	1526
WI	143	305	750	528

Conclusion

This work presents an eco-efficient approach for converting spent yeast waste into two high-value fractions: protein and β -glucan potent molecules. The extraction process yielded fractions of high purity, functional stability, and unique bioactivities. The recovered protein extract provides significant nutritional benefits, while β -glucans exhibit strong immunomodulatory and radical-scavenging properties, highlighting their potential as raw materials in nutraceutical and functional food products. Their thermal stability confirms their suitability for applications requiring heavy processing and long-term storage. Furthermore, extraction efficiency, stability, and targeted delivery were enhanced via the DIC process and nanoencapsulation strategies. Importantly, the sustainability assessment (PMI, ESI, WI) demonstrated a significant improvement in efficiency over conventional methods, reflected in reduced material, water, and energy consumption.

Beyond these technical findings, the study underlines its broader impact by contributing to circular bioeconomy goals, reducing industrial waste, and supporting public health by providing sustainable active ingredients for the food, nutraceutical, cosmetic, and pharmaceutical sectors.

Acknowledgements

This work was supported by the Lebanese American University President's Intramural Research Fund PIRFI0031.

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⁹Oliveira Ana Sofia et al., "Spent Yeast Valorization for Food Applications: Effect of Different Extraction Methodologies," *Foods*, 11, no. 24 (2022): 4002 <https://doi.org/10.3390/foods11244002>.

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Chapter 40

Innovative Invasive Cactus Management: A Sustainable Solution for Kenya's Rangelands

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Abstract

Invasive plant species are non-native species whose introduction and proliferation threaten biodiversity and ecosystem services. Invasive spiny cactus species are causing severe ecological damage in Kenya's rangelands, particularly in Laikipia North Sub-county. Their uncontrolled spread displaces native flora, disrupts ecosystems, and threatens pastoral livelihoods. The current management strategies, such as physical removal and biological control are costly, labour-intensive, and ineffective at large scales. Our innovative solution tackles this problem by converting invasive cactus into nutritious livestock feed pellets. Preliminary trials show promising results: goats fed cactus pellets gained up to 9 kg in 91 days. This approach not only controls invasive species but also provides pastoralists with a low-cost, sustainable feed alternative through the incorporation of spineless cactus and better use of the perennial grasses. The intervention has a broader potential societal impact that addresses poverty, food security, land degradation, and climate action, which are key UN Sustainable Development Goals (SDGs 1, 2, 13, 15). We aim to scale this research into a large-scale ecological and economic solution by producing cactus pellets for livestock farmers in rangelands. Promoting agro-processing technology could also create jobs and empower communities. The innovation is scalable and cost-effective in that pellet production offers a self-sustaining solution with revenue potential. Cactus pellets production can support community empowerment in agro-processing, creating green jobs (especially for women and youth) and turning an environmental threat into a valuable resource, offering a win-win for ecosystems and farmers.

Keywords: *Ecosystem Services, Sustainable Feed Alternative, Women and Youth Empowerment, Food Security, Improved Livelihoods*

Introduction

Arid and semi-arid lands (ASALs) cover over 65% of the Kenyan land mass¹. These areas are hotspots of food and nutritional insecurity, and socio-economic marginalisation. The *Cactaceae* family includes several species adapted to ASAL areas due to their high degree of resistance to drought and high temperatures, adaptability to soils with poor fertility, and excellent productivity due to high water-use efficiency.

¹Vision 2030, Development Strategy for Northern Kenya and other Arid Lands. Strategy of the Government of the Republic of Kenya, 2012 <https://faolex.fao.org/docs/pdf/ken179242.pdf>.

Historical records indicate that the spiny *Opuntia stricta* was introduced to Kenya in the 1890s by railway construction workers as fences to shield them from wild animals². Devoid of natural predators in Kenya, the non-native cactus proliferated unchecked into Kenyan rangelands. This invasion was further facilitated by a combination of factors such as prolonged droughts associated with climate change, the sedentarisation of pastoral communities, and subsequent rangeland degradation from overgrazing³.

The invasive cactus infestation has contributed to a complex socio-ecological challenge that extends beyond rangeland degradation to encompass food security, livelihoods, and human-wildlife conflict. The plants negatively impact biodiversity by outcompeting native grasses and browse species, thereby reducing available forage for both domestic animals and wildlife. Seasons of drought compels both the domestic and wild animals in the rangelands to consume *Opuntia* cladodes and fruits due to lack of alternative forage. This has significant detrimental effects, including mechanical injuries from spines and glochids that cause oral lesions and gastrointestinal distress, a condition known as 'cactus tongue', which can result in mortality. Paradoxically, this foraging behaviour by domestic animals facilitates cactus' dispersal. Secondary dispersal is further aided by birds, elephants, and baboons⁴. Currently, the invasive species *Opuntia* is a critical threat to Kenyan rangelands, occupying 70% of local grazing lands, notably in Laikipia, Baringo, Machakos, Makueni, Narok, and Taita Taveta counties. Its dense thickets impede access to essential resources and have been shown to cause substantial economic losses (US\$500–1000/household/year)⁵.

Control of invasive cactus has been achieved either by chopping using machetes, manual uprooting and burying, use of herbicides, burning or biological control using the cochineal insects, but with limited success^{6,7}. The continued spread of cactus despite these efforts underscores the need for innovative approaches for the management of the invasive cactus. Existing research demonstrates that dietary supplementation with cactus enhances performance in ruminants, including goats⁸ and camels⁹. To

²Ivens, G. W., East Africa weeds and their control. Nairobi: Oxford University Press, 1967

<https://www.scirp.org/reference/referencespapers?referenceid=3266264>

³Githae, E. W., "Status of *Opuntia* invasions in the arid and semi-arid lands of Kenya." Perspectives in Agriculture, Veterinary Science, Nutrition and Natural Resources 13, no. 3 (2018): 1–7.

⁴Witt, A. B., et al., "A preliminary analysis of the costs and benefits of the biological control agent *Dactylopius opuntiae* on *Opuntia stricta* in Laikipia County, Kenya," *BioControl*, 65, no. 4 (2020): 515–523.

⁵Shackleton, R. T., et al., "Distribution and socio-ecological impacts of the invasive alien cactus *Opuntia stricta* in eastern Africa," *Biological Invasions*, 19, no. 8 (2017): 2427–41.

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⁶Witt, A. B., et al., "A preliminary analysis of the costs and benefits of the biological control agent *Dactylopius opuntiae* on *Opuntia stricta* in Laikipia County, Kenya," 515–523.

⁷Shackleton, R. T., et al., "Distribution and socio-ecological impacts of the invasive alien cactus *Opuntia stricta* in eastern Africa," 2427–41.

⁸Pinheiro, Rafael S B, et al., "Physicochemical Quality and Fatty Acid Profile in the Meat of Goats Fed Forage Cactus as a Substitute for Tifton 85 Hay," *Animals (Basel)*, 13, no. 6 (2023): 957

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⁹Ikanya, L. W., et al., "Feed intake, milk yield and milk composition of Somali camels supplemented with *Opuntia stricta* and urea," *Acta Horticulturae*, no. 1343 (2022): 207–12

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address the dual challenges in the pastoral rangelands of invasive cactus and livestock feed scarcity, especially during drought periods, this project introduced an innovative solution. This was through transforming the invasive *O. stricta* into a valuable resource as livestock feed. The main objective was to pelletize spiny *Opuntia* cladodes, enhancing safety and palatability as a livestock feed. This approach not only helps in managing the invasive cactus in the Kenyan rangelands but also produces a storable product that can minimise livestock losses for pastoralists in the ASALs.

Experimental Design and Treatments

The study was conducted at a selected household in Laikipia County, Kenya from October 2024 to January 2025. Thirty-five weaner castrated male goats of the Galla breed with an initial body weight (BW) of 18 ± 3 kg were used. The animals were arranged in a randomised complete block design. Goats ($n = 35$) were individually housed in half-shaded stalls fitted with feeding, water, and mineral troughs. Animals were randomly assigned to five different treatments: (1) Hay only (control) (2) Hay + 1.5% pellets based on BW, (3) Hay + 3% pellets based on BW, (4) Hay + 4.5% pellets based on BW, and (5) Grazing (current practice). Pellets were processed from the invasive cactus available in the study area.

Production of Cactus-based Pellets

Cactus cladodes were harvested by cutting the plants at ground level to produce the pellets as indicated in the schematic protocol (Figure 1). The pads were crushed using an MCTn[®] machine (Laboremus, Campina Grande, Brazil; Figure 2). The crushed material was spread in a thin, uniform layer on black tarpaulin sheets under direct sunlight and turned to promote even drying (Figure 3). Once dried, they are ground using a hammer mill (Figure 4). The milled cactus was mixed with feed-grade urea and ammonium sulphate based on the cactus dry weight, homogenized and processed through a pelleting machine (Figure 5). Fresh pellets were sun-dried until completely free of moisture, weighed, packed in airtight bags, and stored in a cool and dry place (Figure 6).

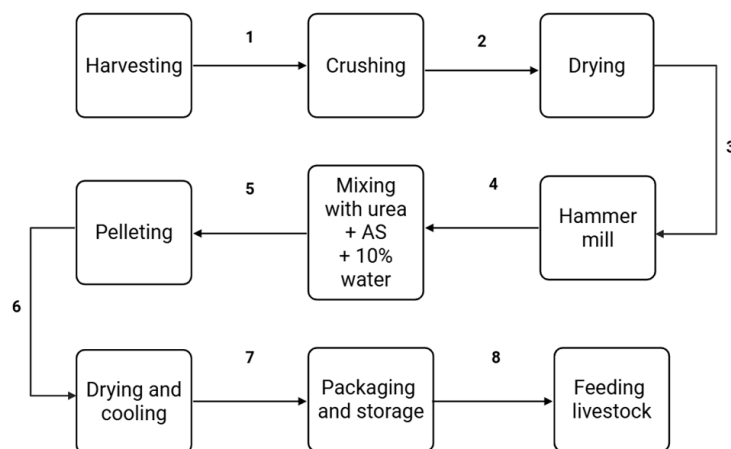


Figure 1: Schematic protocol for producing cactus-based pellets, illustrating sequential steps from harvesting to final feeding.

Machines used for Production of Cactus Pellets



Figure 2: MCTn® machine (Laboremus, Campina Grande, Brazil) used for crushing cactus.



Figure 3: Chopping of the invasive cactus and drying in open field.



Figure 4: Hammer mill used for milling the dried cactus pads.



Figure 5: Pelleting machine used for pelleting the mixture into cactus-based pellets.



Figure 6: The ready to use cactus-based pellets.

Animal Feeding Protocol

- a. Goats were provided hay *ad libitum* and a predetermined supplement of cactus pellets for a period of 91 days.
- b. Due to presence of urea in the pellets, a 21-day step-up adaptation protocol was used. The pellet supplement was introduced at 20% of the target dose and gradually increased until the full amount was reached.
- c. The quantity of pellets offered was adjusted every 14 days based on animal weights. The daily pellet ration was split equally and offered at 8:00 am and 4:00 pm.
- d. Hay and pellet orts were collected and weighed daily before the fresh feed was provided. Mineral mix and water were available *ad libitum* throughout the study.

Results and Discussion

Goat Performance

The inclusion of cactus-based pellets in the diet of male Galla goats exerted a significant, positive linear effect on growth performance and body dimensions. Although hay intake decreased, total dry matter intake as a percentage of BW more than doubled, increasing from 2.1% (control) to 5.1% (4.5% group) ($P < 0.0001$). Body condition, visually assessed and quantified through measurements, improved significantly (Figure 7). A pairwise comparison confirmed that pellet-supplemented goats outperformed those grazing on natural rangelands across all measured growth parameters. The linear increase in pellet intake with supplementation rate and concurrent decline in hay intake is a typical substitution effect, suggesting that cactus pellets were accepted and preferred. Increasing levels of supplementation, particularly concentrates, led to a reduction in basal diet intake due to substitution effects in other studies^{13, 14}. The key findings demonstrated that goats supplemented with cactus-based pellets achieved nearly double the weight gain compared to goats grazing freely, showing significantly improved average daily gain and overall body condition.

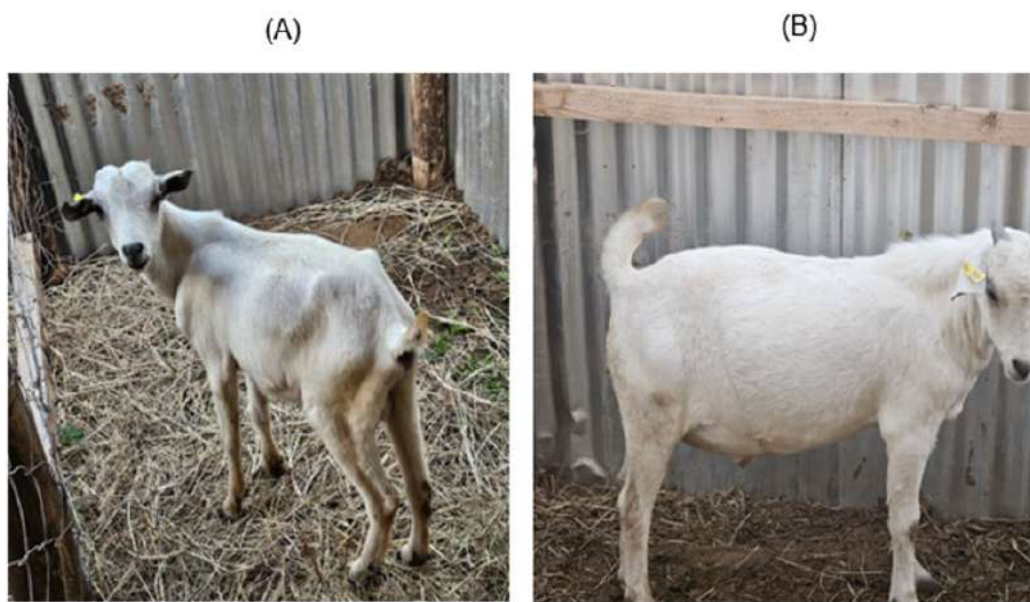


Figure 7: Visual comparison of goat performance under different feeding regimes. (A) Goat fed exclusively on Boma Rhodes hay, exhibiting poor body condition with visible skeletal features. (B) Goat fed Boma Rhodes hay supplemented with cactus-based pellets at 4.5% of body weight, showing improved body condition with fuller musculature and smoother body contours. (Photo credit: Kenneth Oduor, Doldol, Laikipia county, Kenya.

Conclusion

Building on the established potential for addressing poverty, food security, land degradation, and climate action (SDGs 1, 2, 13, 15), future aspects of the study will focus on

- a. mapping and optimizing the entire value chain from harvesting logistics to pellet production, distribution, and end-user sales.

- b. Developing low-cost, modular, and off-grid compatible pelletizing machinery suitable for remote, arid regions. Solar-powered or biofuel-driven systems would enhance resilience and reduce operational costs.
- c. Conducting extended, multi-species feeding trials (cattle, sheep, camels) to determine optimal inclusion rates of cactus pellets in rations, monitor long-term animal health and assess impacts on meat/milk quality and yield.
- d. Long-term ecological studies to quantify the recovery of native rangeland biodiversity following sustained cactus removal and replacement with spineless cactus and native grasses/forages.
- e. Translating findings into actionable policy recommendations for rangeland management, invasive species control subsidies, and support for decentralized agro-processing.

Strategy for Scaling the Innovation.

We have put in place a number of steps in upscaling our innovation. These include:

1. Intellectual property protection for the cactus pellets process and products
2. Compliance with regulations from different government agencies
3. Setting up of a pilot processing plant in Laikipia as it is in the heart of the rangelands, close to target market and invasive cactus raw material source. A pilot plant de-risks the full-scale investment.
4. Marketing of the pellets as sustainable, eco-friendly, and cost-effective.
5. Sourcing of the cactus in phases. Phase 1 (invasive cactus harvesting): Through partnerships with county governments (e.g., Laikipia and Baringo) and NGOs (e.g., Northern Rangelands Trust, Laikipia Wildlife Forum), we will engage the community in harvesting the cactus. Phase 2 (cultivation), we will partner with farmers to grow spineless cactus on their land under contract.
6. Sourcing of funding to support the establishment of the pilot plant, including Capital Expenditures (CAPEX) estimated at US\$ 250,000 and Operating Expenditure (OPEX for 1st year) estimated at US\$ 100,000.

Potential Limitations and Operational Risks

	Factor	Risk	Mitigation
1.	Cactus pads	Nutrient fluctuation between seasons	Storage facilities
2.	Supply chain volatility	Unpredictable harvesting	Transition to spineless cactus
3.	Shelf life	Spoilage due to inadequate drying	Quality control during drying and adequate storage
4.	Cultural resistance	Skepticism of new feed	Establish demo farms and champion farmers

	Factor	Risk	Mitigation
5.	Price sensitivity	Cautious market	Articulate that it is a drought insurance
6.	Competition	Copying of product by competitors	IP protection
7.	Ecological threat of the invasive cactus	Unintentionally incentivise people to propagate	Harvest from pre-approved, mapped areas of infestation and monitor to prevent regrowth
8.	Water use in cultivation of cactus	Competition with other needs	Adopt efficient irrigation systems

Acknowledgements

The funding support for this study was provided by University of Florida and the dryGrow Foundation.

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Chapter 41

Next-generation Community Hubs for Socio-economic Empowerment: A Pilot Human-centred Framework and Participatory Digital Twin Approach

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Abstract

The University of Cincinnati's (UC) Future Mobility Design (FMD) Lab, in collaboration with the Ohio Department of Transportation (ODOT), developed a human-centred research (HCR), data-driven methodology to help communities and decision-makers co-create future-ready hubs that integrate transportation with access to healthcare, education, employment, and other essential services. The framework includes three components: a mixed-methods approach for data collection, a hubs typology matrix based on land-use and community needs, and a translation framework that enables stakeholders to design local hubs. Outputs include nine immersive digital twins (DTs) and the Future Hub Playbook, a participatory guide for inclusive stakeholder engagement. While full co-design workshops are planned for the next research phase, this pilot highlights the potential of combining mixed-methods and simulation technologies to empower communities and facilitate inclusive planning. The framework is currently being adapted with global partners, including the MIT City Science Network, for implementation across the U.S., the Global South, and Europe.

Keywords: *Community hubs, Digital twins, Human-centred, Design, Participation*

Introduction

Rapid urbanisation and accelerating technological change are reshaping how people live, move, and access services worldwide¹. Traditional planning often overlooks local realities, perpetuating exclusion and access disparities². These complexities require a new bottom-up approach that integrates community knowledge, data, and democratized planning³. Enhancing participatory processes with digital technologies can help bridge gaps in participation and access. Future hubs, multifunctional mobility and community centres, are used in this chapter as a case study due to their systemic potential and adaptability.

¹Hannon et al., "An Integrated Perspective on the Future of Mobility," McKinsey & Company (2018) <https://www.mckinsey.com/business-functions/sustainability-and-resource-productivity/our-insights/an-integrated-perspective-on-the-future-of-mobility>.

²Holmes et al., "Mismatch: How Inclusion Shapes Design", MIT Press (2018).

³Durand et al., "Access Denied? Digital Inequality in Transport Services," Transport Reviews 42 (2021): 32–57 <https://doi.org/10.1080/01441647.2021.1923584>.

This chapter presents a design-driven methodology developed by UC's FMD Lab, in partnership with ODOT, to co-create multifunctional, future-ready hubs that integrate transportation with essential services. Grounded in HCR and powered by DTs, the framework comprises three phases: 1. Mixed-methods methodology for participatory and context-aware data collection, 2. Translation framework to integrate data into design recommendations, and 3. Simulation tools for accessible stakeholder involvement. The research question is: How can HCR methods and emerging technologies enable participatory development of sustainable future hubs? This research contributes to participatory planning literature by embedding simulations and qualitative research into replicable, policy-aligned toolkits.

Background: Addressing Access Gaps Through Future Hubs

Global Access Inequities

Traditional car-centric planning, limited infrastructure, and exclusionary zoning have disproportionately impacted underserved communities. These environments restrict quality of life and reinforce barriers to essential services⁴. New global planning strategies emerge in response to the failures of the past and the demands of the future by addressing the diverse needs of urban, suburban, and rural populations⁵. Inclusive and participatory tools emerge as needed catalysts to bridge the access gap⁶.

Future-ready Hubs

Future hubs serve as community anchors, integrating transport with essential services like education, healthcare, recreation, and commerce. Their impacts include economic resilience, equitable access, and spatial inclusion. While established frameworks for planning exist, stakeholder engagement remains underdeveloped⁷, and few models enable communities to co-design these environments meaningfully.

Participatory and Tech-enabled Planning

Participatory co-design and stakeholder research are essential for tackling complex societal issues. These processes depend on collaborative, accessible tools that empower communities to shape planning outcomes⁸. DTs provide immersive, low-cost visualisations of spatial and social data, enabling deeper

⁴Hannon, et al., "An Integrated Perspective," (2018).

⁵"Global Street Design Guide". Global Designing Cities Initiative. Island Press, (2016).

⁶Bui et al., "Full Inclusive Participation (FIP) Approach: Design Process Case Study in Urban Mobility." Cumulus Association Conference Ethical Leadership, (2025).

⁷Pinheiro, "Multimodal Transport Hubs: Good Practice Guidelines. *Agence française de développement*," (2020) www.mobilisyourcity.net/sites/default/files/2020-09/multimodal-transport-hubs-good-practice-guidelines.pdf.

⁸Sanders et al., "Co-Creation and the New Landscapes of Design." *CoDesign* 4, (2008). <https://doi.org/10.1080/15710880701875068>.

engagement, understanding, and consensus-building. When integrated into participatory processes, they help stakeholders visualize, explore, and shape potential futures⁹.

Methods: Developing HCR and Data-driven Frameworks

Hubs Definition

To identify potential hub typologies across Ohio, an IRB-approved study was conducted using mixed methods: primary research (stakeholder interviews, surveys, site visits¹⁰) and secondary research (STEEP analysis¹¹ and trends forecasting¹²), uncovered current mobility experiences/challenges, and opportunities for future hubs (Figure 1). Data included 81 survey responses from stakeholders across Ohio¹³, 20 expert interviews from the U.S., and multiple site visits (Figure 2).

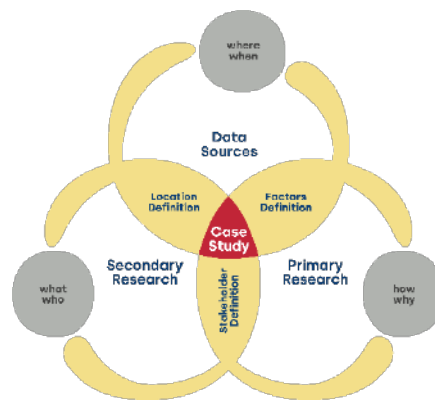


Figure 1: Case Study Definition.



Figure 2: Primary Data Collection.

These inputs revealed gaps, preferences, and infrastructure needs, leading to defining nine hub case studies and a Typology Matrix that accounted for urban, suburban, and rural land use, alongside levels of connection and size. The matrix was cross-validated with GIS data and planning tools from the UC Infrastructure Institute¹⁴ (Figure 3).

⁹Lozano Robledo et al., “Digital Twins in Co-Design Workshops,” *IDSA*, (2024).

¹⁰Kumar, “101 Design Methods: A Structured Approach for Driving Innovation in Your Organization,” *John Wiley & Sons*, (2013) https://www.researchgate.net/publication/328861557_101_Design_Methods.

¹¹Fisher et al., “STEEP,” In *Strategy in 3D*, *Oxford University Press*, (2020) <https://doi.org/10.1093/oso/9780190081478.003.0006>.

¹²Hannon, et al., “An Integrated Perspective,” (2018).

¹³Kumar, “101 Design Methods,” *John Wiley & Sons*, (2013).

¹⁴Bonthu et al., “A Framework for Real-Time Road User Safety with Computer Vision and Vehicle-to-Everything (V2X) Alerts,” *University of Cincinnati*, (2024) http://rave.ohiolink.edu/etdc/view?acc_num=ucin1721398325731484.

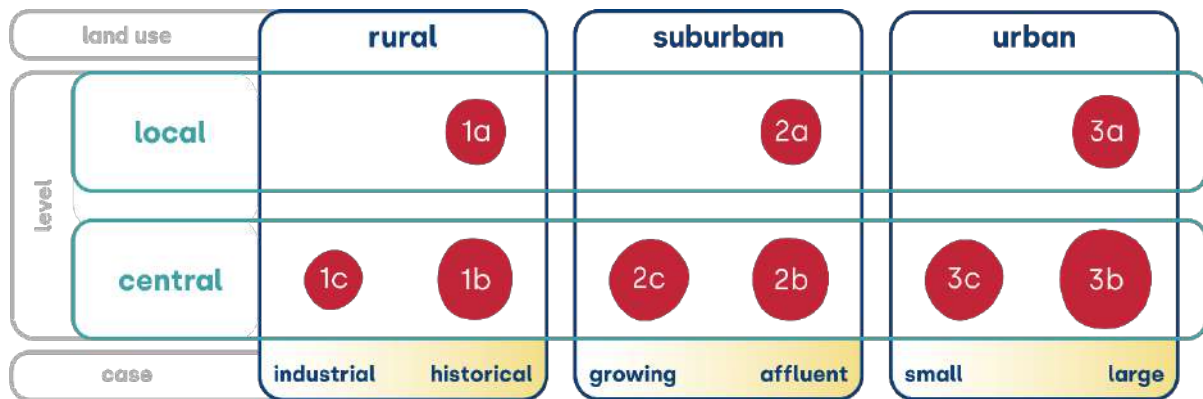


Figure 3: Typology Matrix.

Translating Data into Design Concepts

The translation framework converted insights into context-specific modules from the Typology Matrix, incorporating requirements from architecture, urban planning, design, user-experience, mobility, and other amenities (Figure 4).

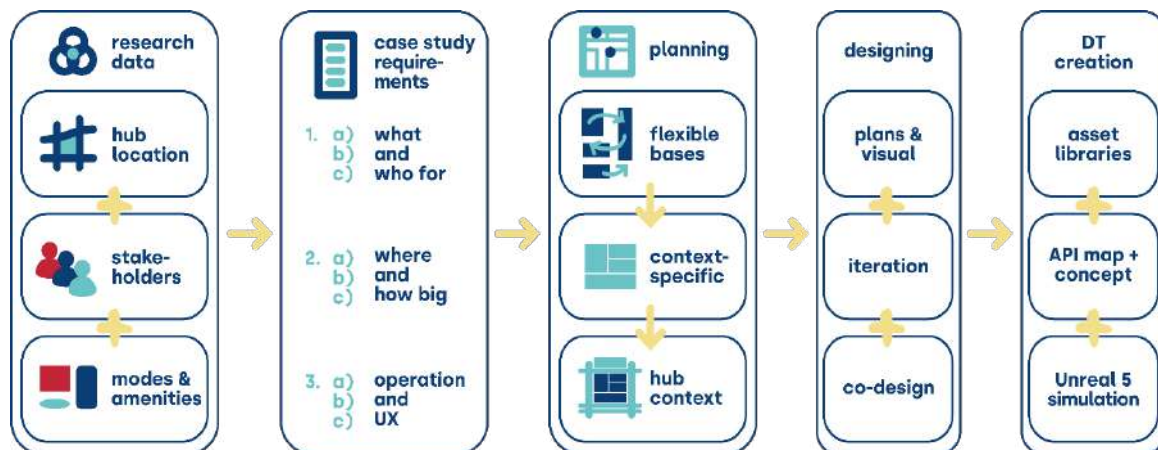


Figure 4: Translation Framework.

The design process included bubble diagrams¹⁵ (Figure 5), which translated floor plans into designs, and concept-sketching and 3D-modeling, which applied aesthetics to create hub concepts. To refine scale, collaborative AR/VR bubble exercises were conducted in Gravity Sketch. Concepts were contextualized with local datasets and validated through research feedback, ensuring designs reflected stakeholder needs and future scenarios.

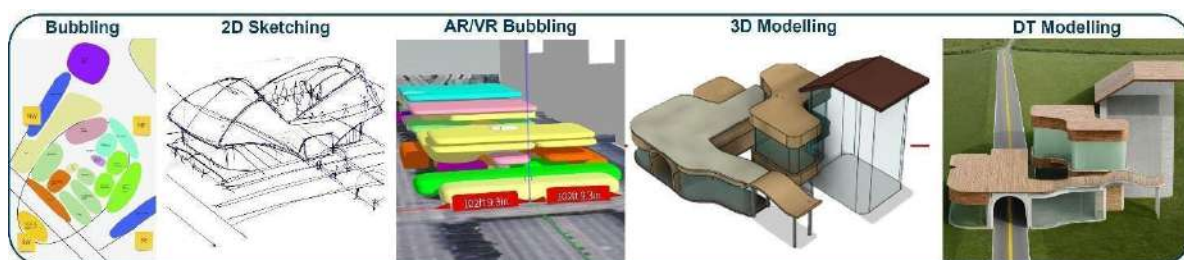


Figure 5: Design Process.

¹⁵Emmons Paul, "The Cosmogony of Bubble Diagrams," *86th Annual Association of Collegiate Schools of Architecture*, (1998): 420–25.

DT Simulation Framework

Using TwinMotion software, and following the typology matrix, DT hubs were created, each combining site topography, design concepts, animations, and environments to produce realistic, walkable, interactive, and VR-compatible simulations (Figure 6). Stakeholders could visualize pedestrian activity, multimodal traffic, architectural features, and amenities in real time. DTs enable a low-barrier entry point for discussion, aligning data, planning, and community vision into a shared language. This framework will enable further workshops where participants co-create future hubs (Figure 7).



Figure 6: DT Process.



Figure 7: Final DTs

Future Hub Playbook: A Participatory Framework for Hub Planning

The Future Hub Playbook is a participatory and data-informed tool designed to translate complex research into accessible planning resources¹⁶. This tool combines the framework from Section 3 and leverages DTs for low-cost simulations, also empowering participatory processes with diverse stakeholders by enhancing the context and leveraging data-driven mixed-use methods.

It translates the research framework into clear prompts, amenity checklists, stakeholder guides, and design concepts, enabling community leaders, planners, policymakers, companies, and nonprofits to collaboratively design future-ready hubs.

Structured for scalability and accessibility, the playbook introduces the theory of future hubs, articulating their role in addressing equity challenges, and outlining a 4-pillar step-by-step planning process for all stakeholders (Figure 8):

¹⁶“Future Mobility Design Lab,” *University of Cincinnati, Office of Research*, (2025).
<https://ucdigitalfutures.com/future-mobility-design-lab/>.

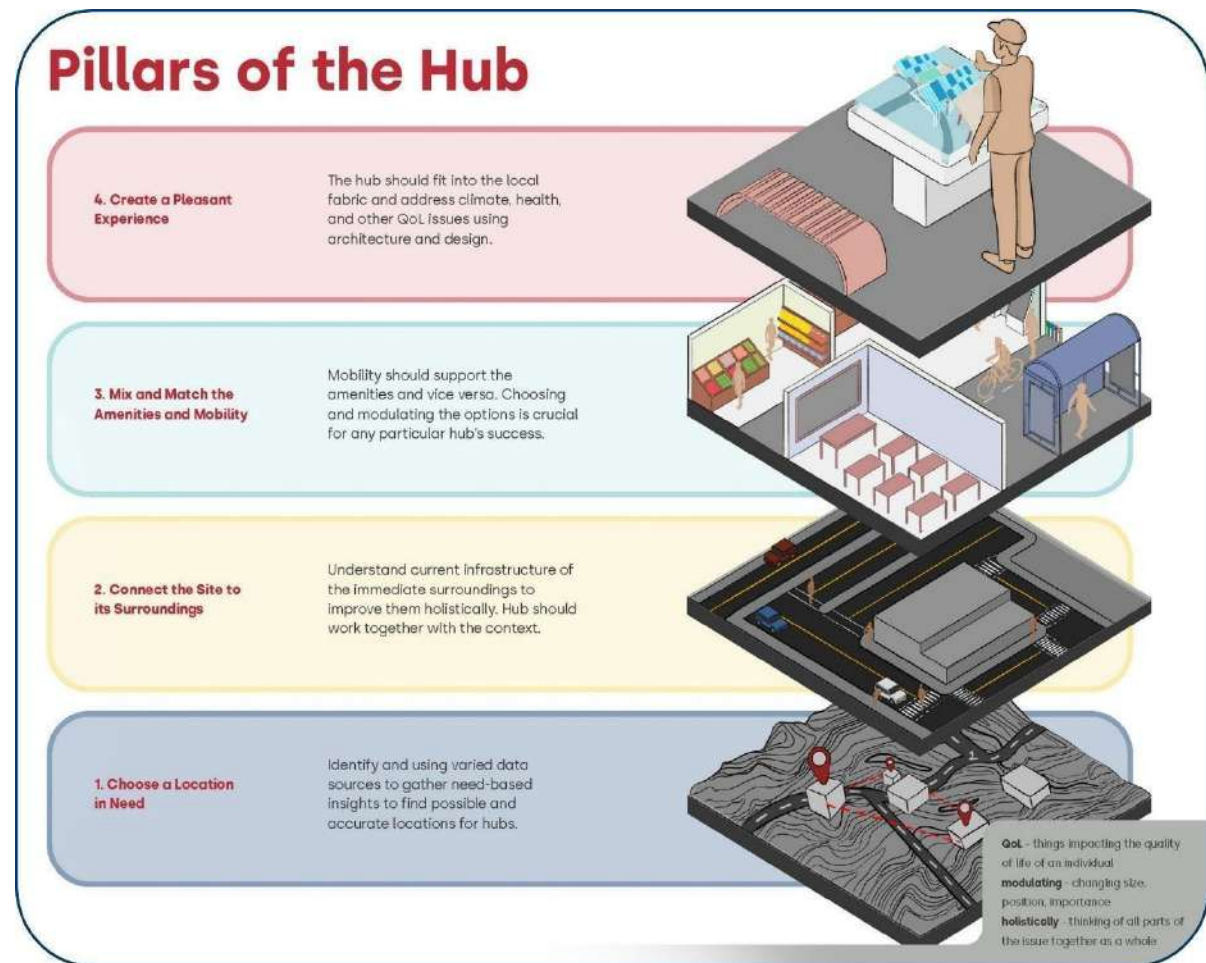


Figure 8: Hub Pillars Overview (1-Choosing location, 2-Connecting sites to surroundings, 3-Combining amenities and mobility, 4-Creating pleasant experience).

Each pillar is supported by research insights, visual DT examples, and checklists that guide stakeholders through design decisions. Rather than dictating solutions, the playbook encourages collaborative adaptation to local contexts. As both a technical and facilitation tool, it lowers barriers to civic engagement by combining HCR, data insights, and immersive technologies (Figure 9, Figure 10, Figure 11).

Although this phase is a methodological pilot, the playbook has undergone multiple revisions. ODOT experts have shown strong interest and are partnering with the FMD Lab to implement it in Ohio communities. The framework has been showcased at four regional events, including at OTEC 2024, ODOT Future Mobility and All Aboard Ohio webinars, and City of Cincinnati Port Authority demonstration. These sessions engaged planners, policymakers, transportation experts, and community members. Feedback has been overwhelmingly positive, and findings are being compiled by the FMD Lab (Figure 12).

1. Choose a Location in Need

Why is this step important?

Choosing the right location that is based on need and demand helps mobility hubs be usable to more people and businesses. It makes sure more people can get to jobs, education, healthcare, and more. Well-placed Hubs help communities grow while being financially and policy-wise efficient and sustainable.

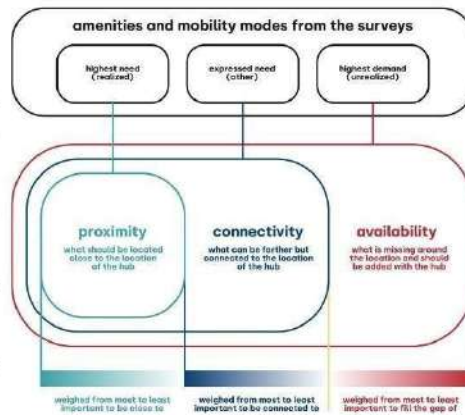
Primary Research to Location

Primary research helps define development priorities by gathering real-world data. Surveys, interviews, and site visits should be conducted. Utilize GIS tools to map their presence and finally cluster according to weight to uncover the right locations.

The Weighing Framework

To cluster, the framework considers proximity, connectivity, and availability of existing mobility, infrastructure and amenities to select and weigh them. The amount of points with certain importance is used to narrow down the location. Proximity consists of places that should be within a 15-minute walk or 10 transit stops from a Hub, connectivity of places that should have smooth road or transit access, and availability of places that do not exist in the first two but should.

This framework ensures hubs are placed where they provide the most value, and make use and connect to existing places without impeding the flows of passengers and goods.



The Weighing Framework

Example of mapped existing places

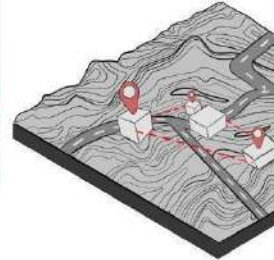


Example of Clustering on a Hub



Consider This

When choosing a location, consider planned land use, ensuring the hub fits current policy and into the surrounding local fabric. Evaluate current mobility options and its infrastructure to enhance connectivity and fill service gaps. Factor in surface parking lots or unused buildings' redevelopment potential to future-proof the Hub.



Action Panel!

Use primary data early to identify specific need, demand, land use, and existing places of interest. Define which places fall into proximity, connectivity, and availability. Use publicly available GIS data to map and narrow down on the final land plots.

2c – Suburban Growing / Central Example: Forest Park, OH

About this Hub

Forest Park, located north of Cincinnati, serves as a central hub within the suburban context due to its growing population and diverse community. Forest Park is a dynamic suburb with a mix of residential, and commercial spaces. Known for its high demographic diversity, the area is home to a blend of cultural backgrounds and socioeconomic groups. The "central" hub in Forest Park focuses on improving mobility for residents, enhancing access to essential services, and providing more sustainable transportation options. It aims to strengthen connectivity within the suburb while supporting its continued growth and development.



Figure 9: Pillars 1 and 2.



Figure 10: Pillars 3 and 4.

Amenities Checklist						
Amenities	Rural Local	Rural Central	Suburban Local	Suburban Central	Urban Local	Urban Central
Government services		○				○
Community center	●	●	○	●	○	●
Recreation center/trail	○	○	●	●	●	●
Park/plaza	●	●	●	●	○	●
Community garden			●	○	●	○
Culture/arts/events	○	○		○		●
Grocery store/market	●	●	○		●	●
Childcare	○	○	○	●	●	○
Healthcare/aging populations	●	●		○	○	○
Education spaces/library		●	○	○	●	●
Offices		●		●		○
Co-working	○				●	●
Retail/entertainment		●	○	○	○	●
Delivery/food delivery		○		○	○	○
Bar/cafe	○	●	○	●	●	●
Restaurant/street food	○	●		●	○	●
Affordable housing/shelter		○			○	●

● Should Have ○ Consider ◻ Not Needed

Figure 11: Stakeholders Checklist.



Figure 12: Validation.

Conclusions: Laying the Foundation for Global Adaptation

This framework offers a replicable model that bridges local knowledge, immersive simulation, and participatory design, creating new pathways for equitable infrastructure development. Three key contributions and future work opportunities emerge:

DTs as Democratising Tools

DTs proved essential for facilitating understanding and stakeholder alignment. Their immersive realism supports data-visualisation, scenario exploration, and community engagement, making complex planning processes more inclusive. Built using game engine platforms, the nine high-fidelity DTs enabled early validations for diverse stakeholders to visualize how land-use, transportation networks, and community amenities converge. Future work includes integrating these tools into XR platforms and developing open-source frameworks for broader adoption, particularly by underserved municipalities.

Future Hub Playbook: An Empowerment Tool

The Playbook transforms research into actionable steps for a wide range of stakeholders, reframing planning as an iterative and inclusive process, empowering communities to identify priorities and engage meaningfully in co-creating context-specific hub solutions. Unlike traditional technical reports, it invites collaboration and adaptability, providing visual tools, checklists, and stakeholder prompts to support informed decision-making. Early feedback from Ohio stakeholders confirmed its scalability and potential for wider use. Future iterations will include modules for public use, training resources, and expanded digital integration.

From Ohio Pilot to Global Application

While rooted in Ohio, the framework is already being adapted globally. Current partnerships with the MIT City Science Network and regional entities in the Global South and Europe aim to adapt the methodology to new socio-political and urban contexts. Future publications will document these adaptations, with co-creation sessions, participatory evaluation, and comparative analysis. The work presented serves as the foundation for an evolving global network of case studies using the proposed core methodologies.

Acknowledgments

This work was funded by the **Ohio Department of Transportation (ODOT)**. Special thanks to Ohio communities, the **UC FMD Lab team**, and participating partners.

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Chapter 42

Weaving Economic Dignity: A Framework for Re-engineering Value with Botswana's Heritage Basketry Artisans

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¹University of Botswana, Botswana

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Abstract

Botswana's celebrated basketry presents a stark paradox, its rich cultural heritage rarely translates into economic dignity for its creators. Master weavers, mainly rural women, have sustained this tradition yet remain in socio-economic hardship, often overshadowed by middlemen. Through fieldwork across three Botswana regions, this chapter examines systemic inequities in existing value chains. It challenges the notion of heritage crafts as mere cultural tokens, arguing for their potential as drivers of national GDP, youth engagement, and sustainable development. This chapter proposes an innovative framework for the socio-economic re-valorisation of indigenous craft economies. Moving beyond market access, it addresses artisan exploitation by integrating four components: 1) Co-designed product innovations respecting heritage while meeting market needs; 2) Fair-trade principles via transparent, community-led governance models empowering artisans; 3) Youth mentorship and digital empowerment for knowledge transfer and market relevance; and 4) Strategic policy recommendations for formal recognition of indigenous craft in national economic planning. This empirically validated approach offers a transferable model for the Global South. By re-engineering Botswana's basketry ecosystem, this research provides a pathway for artisans to become primary beneficiaries of their economic futures, not just cultural custodians. This work contributes to discourse on creative economies and ethical value chains, and to sustainable development at the intersection of innovation and living heritage.

Keywords: *Design Heritage, Creative Economy, Botswana, Value Chain, Indigenous Knowledge*

Introduction

Across the Global South, heritage crafts are often celebrated as emblems of national identity, yet this recognition seldom translates into economic security for the artisans themselves. This chapter addresses this paradox through the specific case of Botswana's basketry, a world-class living heritage sustained predominantly by rural women who remain marginalised within its value chain. While studies note that the handicraft sector is a major employer in many developing nations¹. Botswana is conspicuously absent from such lists, highlighting a critical gap between cultural potential and economic reality.

¹Grobar, Lisa M, "Policies to Promote Employment and Preserve Cultural Heritage in the Handicraft Sector," *International Journal of Cultural Policy* 25, no 4 (2019): 515–27 doi:10.1080/10286632.2017.1330887.

Situated at the intersection of Botswana's cultural heritage and its economic development aspirations, this research confronts a critical disconnect. It poses the core question: How can a cross-disciplinary framework re-engineer value for heritage basketry artisans in a way that translates into economic dignity and structural change? This chapter's primary contribution is an empirically grounded, practice-oriented framework designed to dismantle these structural inequities. Anchored in theories of the creative economy² and Amartya Sen's concept of *Development as Freedom*³, this research moves beyond academic critique to present a tangible model informed by early signs of implementation and impact.

Botswana Basketry in Context

The basketry of Botswana holds a global reputation for its intricate beauty and exceptional craftsmanship⁴. They are mostly made by women (see Figure 1). Historically, these objects served symbolic and utilitarian roles, from storing grain to celebrating the harvest⁵. The modern craft revival in the 1970s, aided by international volunteers and NGOs, positioned these baskets in luxury global markets⁶. However, this history also reveals a pattern of external dependency and internal neglect. The departure of foreign support has resulted in a downturn, exposing a deficit in local support systems⁷.

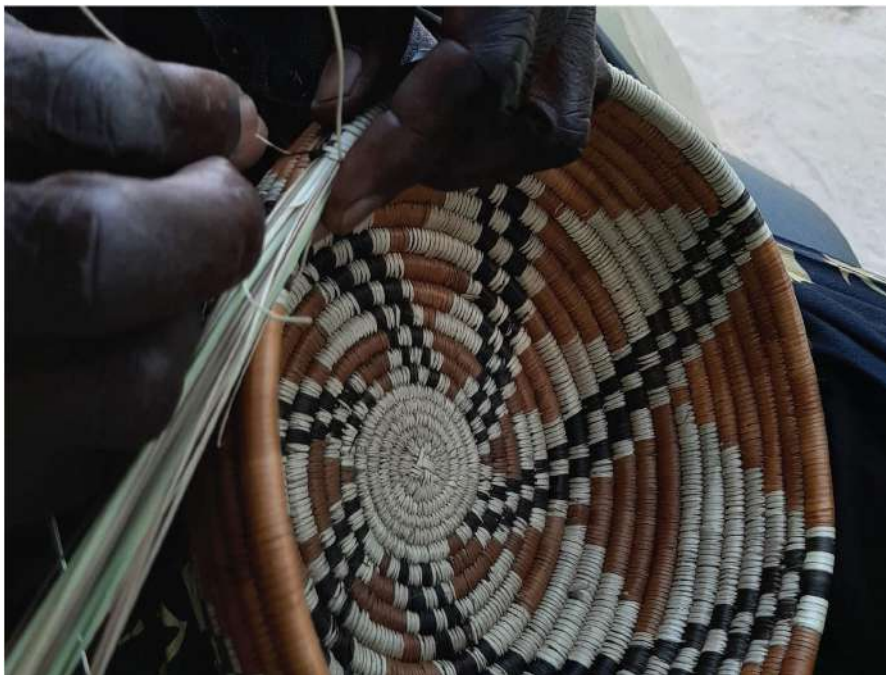


Figure 1: Female artisan weaving a basket in the Okavango Delta region.

²United Nations Conference on Trade and Development (UNCTAD), *Creative Economy Outlook 2022: The Creative Economy for Sustainable Development*. (Geneva: United Nations, 2022), 11, https://unctad.org/system/files/official-document/ditctsce2022d1_overview_en.pdf.

³Amartya Sen: *Development as Freedom*. (Oxford University Press, 1999), 87

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⁵Tlou, T and Campbell, A: *History of Botswana*. (Macmillan Botswana, 1984). 212.

⁶Terry, M. E: *Botswana craft*. (Botswana Craft Marketing Co Gaborone, 1999).

⁷Joseph E Mbaiwa., "The socio-economic and environmental impacts of tourism development on the Okavango Delta, north-western Botswana," *Journal of Arid Environments* 54, no. 2, (2003): 447-467, <https://doi.org/10.1006/jare.2002.1101>.

This was compounded by a policy vacuum. The National Policy on Culture (2001) is over two decades old and lacks implementation, while the nation's key development roadmap, Vision 2036, mentions 'culture' only in passing and 'heritage' not at all. This policy gap stands in stark contrast to other nations such as Thailand, Vietnam, Ethiopia where the craft industry is recognised as a critical economic driver, employing over 10% of the labour force⁸.

This paper argues that this systemic neglect represents a significant missed opportunity for Botswana's socio-economic development.

Research Methodology

The framework proposed in this chapter is grounded in empirical research. The research utilised a qualitative, interpretivist research design⁹ to understand the lived realities of basket weavers. Data were collected through semi-structured, one-on-one interviews and field observations. Through purposive and snowball sampling, 37 basket weavers (aged 35-80+) were recruited from three diverse regions, that is, the North, eastern part of Bobirwa, and Kweneng west (see Figure 2). Twenty-two participants from North region, 10 Bobirwa in the eastern part of Botswana and Kweneng west. All participant names have been replaced with pseudonyms to ensure confidentiality. The thematic analysis was conducted using an inductive approach, moving from codes to themes¹⁰.

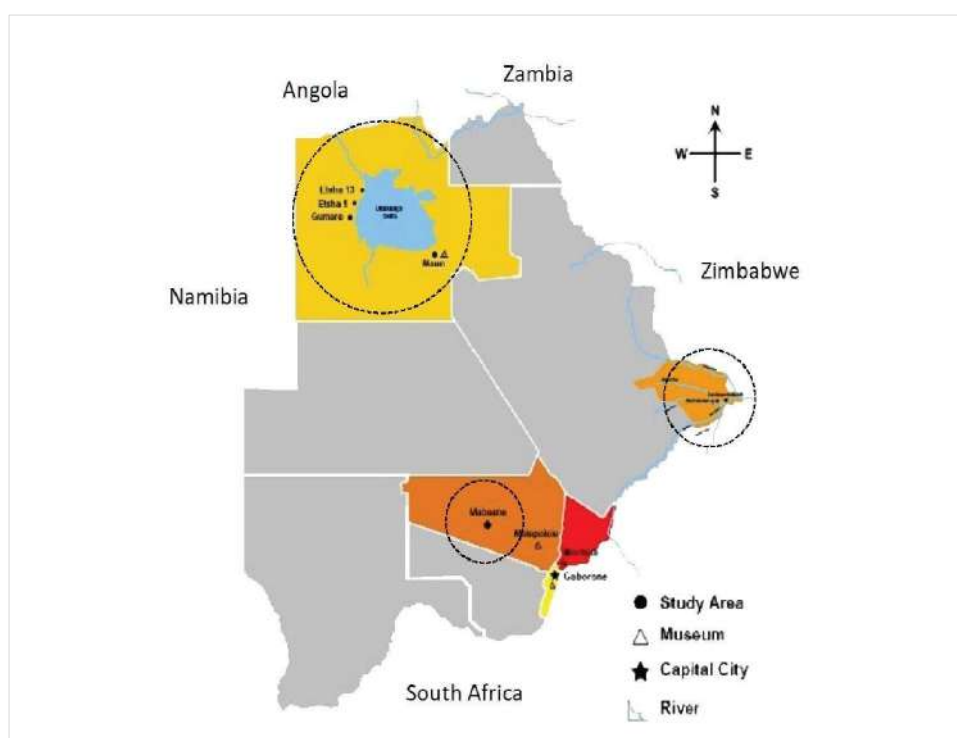


Figure 2: Map of Botswana showing three study areas for this study.

⁸Chudasri, Disaya et al., "Potential areas for design and its implementation to enable the future viability of weaving practices in northern Thailand." *International Journal of Design* 14, no. 1 (2020): 95-111 <https://e-space.mmu.ac.uk/625669/>.

⁹John W. Creswell, *Research Design: Qualitative, Quantitative, and Mixed Methods Approaches*, 4th ed. (Thousand Oaks, CA: SAGE Publications, 2014).

¹⁰Braun, Virginia, and Victoria Clarke, "Using Thematic Analysis in Psychology," *Qualitative Research in Psychology* 3 no 2 (2006): 77-101 doi:10.1191/1478088706qp063oa.

Results

The findings from the interviews are structured into four emergent themes that detail the systemic barriers preventing artisans from achieving economic dignity.

Theme 1: Systemic economic disempowerment

A primary finding is that weavers are systematically disconnected from the final market value of their work, trapping them in a cycle of subsistence. One weaver lamented: *"The middleman comes and gives us food for the basket. We do not know the price in the city"* [P1]. *"We are weaving for food, not for a future."* [P2]. Another described how this dynamic forces them to accept exploitative prices: *"When it is time for the middleman to buy, he will start condemning my product until I give it away for nothing. Because of hunger, I will then settle for anything so that I bring food to the table at home"*. [P3].

Theme 2: Erosion of intergenerational knowledge

The research revealed a profound fear among elders that their unique heritage skills are on the verge of disappearing. A participant from Gumare shared, *"Uhhh... I have fear and we are getting old, tomorrow we will be gone. This young generation is not interested in the work we do... our wish is we want the next generation to make it better."* [P4]. Makers in Bobirwa stated that *youth often prefer government work programmes*, stating, *"They are saying there is no money in basketry"* [P5].

Theme 3: Isolation and lack of a supportive ecosystem

Artisans typically work in isolation from their homes, lacking the collective bargaining power of a guild. This is exacerbated by the departure of NGOs and international volunteers. A weaver from Etsha 6 described this abandonment: *"As you see us, they have left us... now I just weave from home. It is not nice alone and it brings laziness"* [P6].

Theme 4: Barriers to innovation and professional development

Participants identified significant barriers to their professional growth, including a lack of training and a deep-seated weariness of extractive research. Weavers in the north expressed a profound sense of frustration: *"We are tired and you [the researcher] are our last hope... to remove us from this poverty"* [P7].

The Cross-disciplinary Framework for Re-engineering Value

This was developed as a response to systemic barriers identified in empirical findings. Through thematic synthesis, its four components (see Figure 3) were designed to counteract specific challenges articulated by artisans. The 'fair-trade and community-led governance' component addresses 'systemic economic disempowerment,' while 'youth mentorship and digital empowerment' targets 'intergenerational knowledge' erosion. This framework represents a bottom-up solution emerging from weavers' realities to create an equitable craft ecosystem.

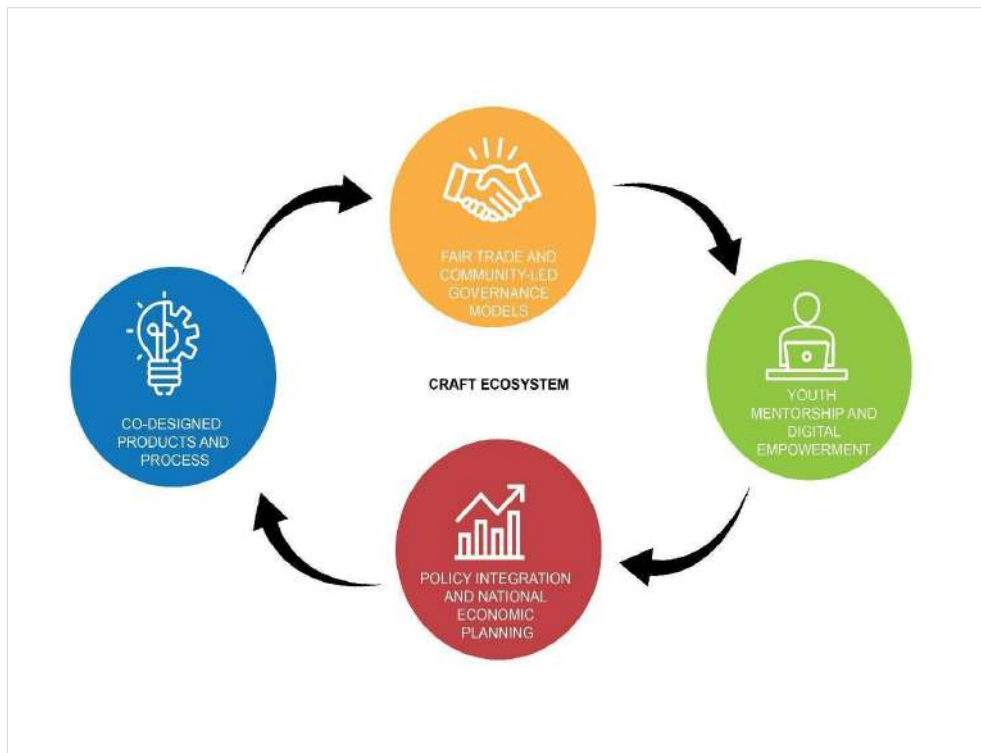


Figure 3: The four-strand framework for re-engineering value.

1. *Co-designed product and process innovations:* Grounded in participatory co-creation, this component focuses on respectfully innovating products to meet contemporary market needs.
2. *Fair-trade and community-led governance models:* To counter exploitation, this component draws on Elinor Ostrom's principles of "commons governance"¹¹ to develop community-led cooperatives that manage pricing and engage directly with buyers¹².
3. *Youth mentorship and digital empowerment:* This component leverages digital tools for intergenerational knowledge transfer and direct-to-consumer sales.
4. *Policy integration and national economic planning:* This component pushes for the formal recognition of heritage crafts within national creative industries policy, anchored in the UNESCO 2005 Convention on cultural diversity.

While proposed for long-term implementation, fieldwork has revealed nascent, artisan-led initiatives that serve as early indicators of impact. Evidence of increased economic returns is emerging; some craftspeople recorded an average 60% increase in products purchased by a corporate sponsor. The most significant outcome, however, is a profound shift in artisan agency. As one weaver stated, "*Before, we were just hands. Now, they listen to our story. I am not just a supplier; I am an expert*" [P8]. This shift reflects the core tenets of Sen's concept of development as the expansion of human capabilities and freedom¹³. There is also evidence of emerging community-led governance and renewed

¹¹Elinor Ostrom, *Governing the Commons: The Evolution of Institutions for Collective Action*, Cambridge University Press, 1990. Accessed September 2, 2025.

https://www.actu-environnement.com/media/pdf/ostrom_1990.pdf

¹²Vaibbhavi Pruthviraj Ranavaade, "Sustainable craft design systems for handloom weavers," *Textile* 20, no. 3 (2022): 399-409 <https://doi.org/10.1080/14759756.2021.1963623>.

¹³Sen, *Development as Freedom*, 87.

intergenerational knowledge transfer, aligning with global efforts to safeguard intangible cultural heritage¹⁴. These indicators provide compelling evidence that artisans are ready to become the architects of their own economic futures.

Discussion

The systemic challenges facing Botswana's weavers market disconnection, policy neglect, and the erosion of heritage, are not unique. They reflect a global pattern in which the cultural value of indigenous craft often struggles to find a foothold in the modern economy¹⁵. However, successful craft revitalisation projects from across the Global South provide a powerful roadmap, revealing a set of common principles for success.

An analysis of these international models, such as Thailand's "One Tambon One Product" (OTOP) initiative, Peru's artisan-cooperative-led textile industry, and Ethiopia's fair-trade certified craft sector, reveals three core pillars that underpin their success. First is the establishment of strong, community-led organisational structures, which move artisans from isolated producers to collective economic agents¹⁶. Second is a strategic commitment to design innovation and quality control, ensuring that heritage products remain relevant to contemporary markets¹⁷. Third, and most critically, is the presence of supportive government policies that formally recognise the craft sector as a vital contributor to the national economy and cultural identity.

Building on these common threads, this chapter proposes a framework that re-valorises indigenous knowledge as the guiding intelligence of the ecosystem. By integrating design, fair-trade governance, digital empowerment, and policy advocacy, it presents a holistic, artisan-centred model. It argues that for development to be truly sustainable, it must be centred on enhancing the dignity and agency of the artisans themselves, not just on increasing their income¹⁸. As such, it presents a transferable and ethically grounded model for other nations seeking to transform their living heritage into a vibrant and equitable economic future.

Conclusions

This chapter has argued that heritage crafts like Botswana's basketry are not nostalgic souvenirs but powerful engines of potential economic dignity. The framework presented here offers a disruptive yet constructive pathway for artisans to become the architects of their economic futures. To achieve this, we must move beyond isolated interventions and towards the cultivation of place-based creative

¹⁴UNESCO, Convention for the Safeguarding of the Intangible Cultural Heritage. 2003.1-14. Accessed January 2, 2025

<https://ich.unesco.org/doc/src/15164-EN.pdf>.

¹⁵Grobar, "Policies to Promote Employment," 520.

¹⁶Ostrom, *Governing the Commons*, 1990.

¹⁷Fang-Wu Tung, "An Entrepreneurial Process to Build a Sustainable Business for Indigenous Craft Revitalization," *The Design Journal*, 24, no. 3 (2021): 363–383. <https://doi.org/10.1080/14606925.2021.1883790>

¹⁸Sen, *Development as Freedom*, 87.

ecologies. This approach acknowledges that empowering artisans is not just about isolated projects, but about fundamentally reconfiguring the power dynamics within the creative process itself¹⁹. Ultimately, this is a call to action for policymakers, researchers, and designers to collaborate on building an ecosystem where the brilliance of Botswana's weavers can finally and truly flourish.

Acknowledgements

I thank Prof. Pammi Sinha, Dr. Eirini Boukla, the University of Botswana for funding, and all participants for their contributions.

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¹⁹Estelle Berger, "Empowering artisans through design: a case study on the dynamics of collaborative projects, in Boess, S., Cheung, M. and Cain, R. (eds.)," *Synergy - DRS International Conference 2020*, (2020): 11-14, <https://doi.org/10.21606/drs.2020.113>.

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Chapter 43

The Re-habitualisation of Boycotts: From Disruption to Everyday Life

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Abstract

Boycotts are commonly framed as momentary acts of resistance, either as tactical disruptions within social movement or as moral expressions in the consumption field. Although widely researched, existing work tends to focus on the mobilisation and impact of boycotts, while overlooking the process that follows. This chapter proposes a new orientation to understand the *re-habitualisation* of boycott, a process through which protest-driven changes in consumption patterns are reconfigured over time. Rather than mere habituation, *re-habitualisation* highlights that daily life is never politically neutral, but a dynamic terrain where political meanings may persist, transform, or dissolve.

To conceptualise this dynamic, I draw on practice theory, which views social life as constituted through routinised practices, making it well-suited to explore post-disruption trajectories. Boycotts are framed as practice performances that interrupt and reconfigure established routines. Methodologically, the analysis is theoretically grounded, with the Fair-Trade movement serving as an illustrative case. This analysis looks into the longer-term trajectories of boycott, while bridging the fields of social movement studies, consumption research, and theories of everyday life.

Keywords: *Boycotts, Social Movements, Political Consumerism, Practice Theory, Everyday Life*

Introduction

The term boycott emerged during the Irish Land War of the 1870s, when tenants refused to deal with Charles Cunningham Boycott, and has since become a widely used tactic from the anti-apartheid struggle to contemporary consumer. Historically, boycotts have long operated both as collective strategies of contention and as everyday acts of political consumption refusal in the marketplace. However, existing research has focused on their mobilisation and symbolic force, while overlooking what happens after the initial disruption.

To address this gap, this article introduces the concept of *re-habitualisation*, the process through which refusals may persist, reconfigure, or fade into new consumption routines. Drawing on practice theory, I argue that boycotts should not be understood merely as intervention tactics, but as practices that could reshape the organisation of everyday life. While primarily theoretical, this chapter also draws on the case of Fair Trade to illustrate how consumer refusals can crystallise into enduring forms of ethical consumerism.

Results and Discussion

Existing Research on Social Movements and Consumption

Social movement scholarship has evolved in its understanding of boycotts over several decades. Early studies positioned boycotts within the *repertoire of contention*¹, emphasising their strategic and disruptive functions. As the field developed, New Social Movement theorists shifted focus toward identity and culture, leading scholars to reframe boycotts as lifestyle politics². While this cultural turn offered valuable insights, it still risks treating boycotts primarily as post-materialist expressions, while overlooking how they may persist after the peak mobilisation periods.

This invites us to look beyond the mobilisation point, to examine the longer-term trajectories. While recent scholarship highlights diffuse, long-term consequences of social movements exist³. This perspective has overlooked how this process may gradually become embedded into ordinary life. Consumer boycotts present a compelling case because they operate directly through everyday consumption practices, making visible how political engagement may (or may not) sustain in the long run.

Boycotts, as a form of political consumption, may begin as deliberate acts but can become repetitive and habitual over time. This dual nature positions them between two models of consumption, deliberative choice, emphasising symbolic display and identity, and habitual practice, rooted in routine and systems of provision. From a processual perspective, this dual nature suggests how boycotts could carry political engagement beyond moments of deliberate choice, becoming embedded in everyday practice.

Micheletti⁴ offered the conceptualisation of political consumerism, framing it as 'individualised collective action'. Crucially, she emphasises that such practices blur the boundaries between private and public spheres, transforming personal market choices into forms of political participation. Once consumption is understood as political participation, its significance rests on attaching ethical meaning to market choices, a move underpinned by the broader ideology of ethical consumerism, which naturalises the idea that individual market actions are both politically and morally charged⁵. This evolution shows how political meanings could be stabilised within consumption practices. However, what remains less understood is how such practices evolve in the long run, a gap this article aims to address.

¹Charles Tilly, *From Mobilization to Revolution* (McGraw-Hill, 1978).

²Melucci, Alberto, *Challenging Codes: Collective Action in the Information Age* (Cambridge University Press, 1996).

³Lorenzo Bosi et al., eds., *The Consequences of Social Movements* (Cambridge University Press, 2016).

⁴M. Micheletti, *Political Virtue and Shopping: Individuals, Consumerism, and Collective Action*, 1st ed (Palgrave Macmillan, 2003).

⁵Clive Barnett et al., 'Consuming Ethics: Articulating the Subjects and Spaces of Ethical Consumption', *Antipode* 37, no. 1 (2005): 23–45, <https://doi.org/10.1111/j.0066-4812.2005.00472.x>.

The Politicalisation of Everyday Life: What Happens Beyond ‘Disruption’

As mentioned above, scholars from both fields have offered valuable insights into boycotts, situating them either as part of contentious politics or as a form of political consumerism in the marketplace. Together, these approaches have explored the symbolic meaning of boycotts, how they mobilise everyday consumption into political struggle, and the outcomes they may generate. However, less attention has been paid to the processes afterwards, on how such refusals unfold in everyday life.

This gap invites attention to everyday life, which has increasingly been recognised as central to political expression and social change⁶. Classic theorists have highlighted how mundane practices are simultaneously structured by dominant systems and reworked through resistance and negotiation⁷. In this sense, what appears ordinary could operate as a powerful orientation for social change.

In particular, boycotting offers a critical site to examine this dynamic. It disrupts existing, habituated consumption patterns, which forces reconsideration of established routines. To capture what happens after such disruptions, this article proposes the concept of *re-habituatisation*: the process through which political refusals are negotiated in the long run, either routinised, transformed into new practices, or fade away. Rather than passive habituation, it draws attention to the continual adjustments of ‘politics’, shifting the focus to the longer-term trajectories (Figure 1).

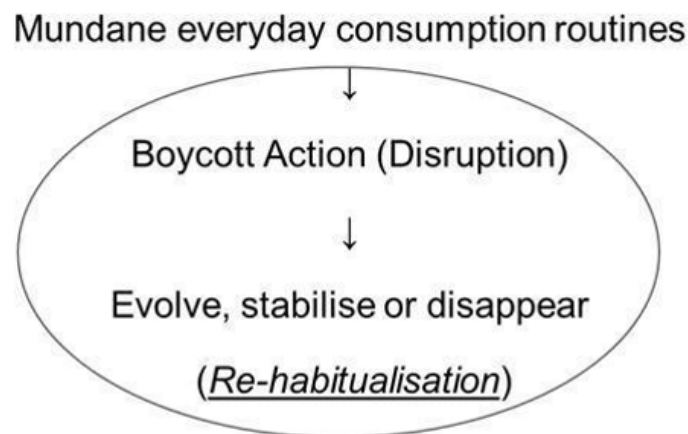


Figure 1: The re-habituatisation process.

Given space constraints, this article does not seek to fully conceptualise re-habituatisation but identifies it as a theoretical gap for future work. As a starting point, practice theory could provide a framework for explaining how refusals may stabilise over time.

Practice Theory: A Framework for Analysis

Practice theory shifts attention from individuals or structures to *social practices*, understood as routinised behaviours, as the basic unit of social analysis⁸. Warde⁹ identifies three key elements of

⁶Michel de Certeau, *The Practice of Everyday Life* (University of California Press, 1984).

⁷de Certeau, *The Practice of Everyday Life*.

⁸Andreas Reckwitz, 'Toward a Theory of Social Practices: A Development in Culturalist Theorizing', *European Journal of Social Theory* 5, no. 2 (2002): 243–63, <https://doi.org/10.1177/13684310222225432>.

⁹Alan Warde, 'Consumption and Theories of Practice', *Journal of Consumer Culture* 5, no. 2 (2005): 131–53, <https://doi.org/10.1177/1469540505053090>.

practice within the context of consumption: procedures, understandings, and engagement. Applied to the re-habitualisation of boycotts, this framework sees boycotts not simply as deliberate refusal, but as evolving practices shaped by gradual shifts in these elements. For example, the understanding of a boycott may shift from a form of collective protest to a personal ethical commitment; procedures such as using boycott apps or checking labels may become habitualised; and engagements may move from initial outrage to a more general sense of care or responsibility. Boycotts, therefore, do more than interrupt established consumption patterns, they should be regarded as practices through which needs and wants are reconfigured.

In discussing the stability and change in practices, Schatzki¹⁰ further distinguishes between *practices-as-entities* and *practices-as-performances*. Practices-as-entities refer to the socially recognisable configurations that define a practice, while practices-as-performances refer to the actual enactments of these practices in everyday life. This conceptualisation enables us to explore how practices evolve and change over time. As performances accumulate and adapt, they may gradually reconfigure the overall entity. In the context of boycott afterlife, this distinction allows us to conceptualise the aftermath not simply as a disappearance or continuation but as a dynamic process of interaction between specific practices (e.g., political consumption) and broader entities (e.g., ethical consumerism), which continually pushes forward the development of how we understand *ethics*.

To further ground this theoretical discussion, the following section draws on the case of Fair Trade to illustrate how boycotts could be re-habitualised into everyday consumption routines.

Illustrative Case: Fair Trade

Although not a boycott itself, Fair Trade could be regarded as part of the afterlife of boycott: it arose in response to campaigns such as the Nike Sweatshop Boycott, offering consumers an ethical alternative. Emerging from faith-based and solidarity trade initiatives in the 1950s-1960s, it later developed into a certification system that made ethical choices more accessible¹¹. Over time, practices such as label checking became embedded in everyday shopping, illustrating how boycott-inspired refusals can stabilise into routinised consumption, an example of re-habitualisation.

As an outcome, ethical consumerism should be understood not as a direct, self-aware moral choice, but as something that gradually re-articulates through repeated, routinised everyday practices¹². Drawing on practice theory, particularly the distinction between practice-as-entity (the broader ideology of ethical consumerism) and practice-as-performance (individual ethical practices in daily life), we can see how repeated practices reshape what counts as 'ethical'. Over time, supported by campaigns, labels, and market narratives¹³, this recursive process embeds political meanings into daily life as taken-for-granted norms. Thus, the meaning of ethical consumerism is never fixed, but continually redefined through the

¹⁰Theodore R. Schatzki, *Social Practices: A Wittgensteinian Approach to Human Activity and the Social* (Cambridge: Cambridge University Press, 1996).

¹¹Klein, Naomi. *No Logo*. HarperCollins UK, 2001.

¹²Barnett et al., 'Consuming Ethics'.

¹³Barnett et al., 'Consuming Ethics'.

interplay of everyday performances and the broader entity they constitute, a spiral, evolving process that illustrates how political practices stabilise in mundane routines.

Limitations and Implications

The re-habitualisation perspective offers valuable insights for both policy and practice. Its focus on everyday routines is particularly relevant to community empowerment and sustainability, highlighting the infrastructures needed to stabilise ethical practices beyond peak protest moments. Rather than relying on episodic mobilisation, policymakers could support local initiatives that embed political meaning in daily consumption, extending the legacy of collective action. In this way, the perspective strengthens civic engagement and fosters more durable participation, grounding policy in ordinary life rather than exceptional events.

While this article introduces re-habitualisation, further conceptual and empirical work is needed to clarify its stages, phases, and outcomes. Attention should also be given to international solidarity, especially in today's post-COVID, de-globalising world, where nationalist boycotts may follow divergent trajectories shaped by contrasting political logics.

Conclusion

This article proposes *re-habitualisation* to explain how boycotts unfold after the moment of disruption. While existing research emphasises the symbolic character of boycotts, I argue that boycotts should be understood as social practices that may stabilise and transform our everyday life. Drawing on practice theory and illustrated through Fair Trade, this perspective highlights how political refusals are continually negotiated, embedding political meaning in mundane routines. By focusing on the politics of the ordinary, re-habitualisation bridges social movement and consumption research, while suggesting directions for future research on further developing the phases and mechanisms of the process.

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Part VI

Open

Chapter 44

Eco-friendly and Biocompatible Materials for Noise Reduction in Healthcare Environments

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Abstract

Noise pollution has been shown to negatively affect the lives of millions of people, resulting in problems such as stress, high blood pressure, hearing loss, and sleep disruption. This issue is of great importance in healthcare spaces, where not only low noise levels are preferable but also a low-toxicity environment is needed. In this context, conceiving innovative solutions that help reduce noise while preserving safety conditions for clinical activity has become a priority among medical industry professionals and the scientific community. Our research proposes an eco-friendly, biocompatible material made from recycled plastic bottles to reduce noise pollution and enhance acoustic comfort in healthcare environments. While plastic production increases significantly every year, its very low recycling rate leads to large amounts of it entering the environment, thus urging the pursuit of sustainable solutions that allow for the reuse of plastic waste. Therefore, by transforming this plastic into PET (polyethylene terephthalate) felt composites, the health risks associated with noise and the environmental challenge are both addressed. Prototype samples were manufactured by an industrial partner and successfully tested in a childcare playroom of the Paediatric Oncology Department of the Hospital Universitario La Paz, in Spain. In doing so, not only was significant noise reduction achieved, but also a positive impact on the well-being of hospitalized children, while also contributing to better preservation of the planet. Preliminary results show the potential of the developed material and encourage us to extend this product to healthcare institutions worldwide.

Keywords: *Eco-friendly Material, Biocompatible Material, Noise Reduction*

Introduction

Reducing the noise pollution has become a priority in a society increasingly aware of its harmful effects on human health¹. Many studies have shown the importance of creating more comfortable and noiseless spaces for our well-being, especially in the case of healthcare environments such as hospitals². In this context, the development of new noise-reducing materials plays a vital role not only to help lower stress and rest disruption but also to guarantee a safe and low-toxicity environment. In fact, the increasing

¹World Health Organization, Burden of Disease from Environmental Noise. Quantification of Healthy Life Years Lost in Europe (WHO Regional Office for Europe, 2011).

²Denise B. Choiniere, "The Effects of Hospital Noise," *Nursing Administration Quarterly* 34, no. 4 (2010): 327–33, <https://doi.org/10.1097/NAQ.0b013e3181f563db>.

demand for this type of product in multiple healthcare projects urges the need to foster collaboration between diverse professionals and organizations.

On the other hand, environmental concerns such as climate change, pollution, and biodiversity loss have increased attention towards the development of production processes to be more respectful for the environment. In this regard, one of the main sources of product waste nowadays is linked to the industry of plastic manufacturing, whose environmental commitment with its collection and recycling has become a priority that aligns with the circular economy principles. While some recent works have shown the potential of prefabricated panels with recycled thermoplastic PET (polyethylene terephthalate) materials³, low-toxicity and biocompatibility were not assessed, thus compromising their safe applicability in healthcare scenarios.

This research is dedicated to the development and analysis of sustainable sound-absorbing acoustic panels made from recycled plastic bottles for their use in healthcare environments, thus combining acoustic comfort with health safety⁴.

Eco-friendly and Biocompatible Material

The eco-friendly and biocompatible material developed consists of acoustic panels made from PET, a plastic widely used in the production of beverage bottles. With more than 5 million bottles recycled last year (up to 75 plastic bottles are recycled to make 1 m² of product), these PET acoustic panels contribute to reducing the amount of plastic waste in the environment while promoting the circular economy. The fabrication procedure is summarised in Figure 1. In brief, the plastic bottles are collected, separated, cleaned, and crushed into small flakes that, after undergoing a heating and extrusion process, produce fine and malleable yarn fibres that can be compacted to form an insulating panel as depicted in Figure 2.



Figure 1: Fabrication process of ECOcero sound-absorbing PET panels (Source: ECOcero <https://ecocero.com/en/>).

³Silvia Cavagnoli et al., "Advancing Sustainable Construction Through Comprehensive Analysis of Thermal, Acoustic, and Environmental Properties in Prefabricated Panels with Recycled PET Materials," *Energy Build*, 312 (2024): 114218, <https://doi.org/10.1016/j.enbuild.2024.114218>.

⁴David del Rosario-Gilabert et al., "Eco-friendly and Biocompatible Material to Reduce Noise Pollution and Improve Acoustic Comfort in Healthcare Environments," *Buildings* 14, no. 10 (2024): 3151, <https://doi.org/10.3390/buildings14103151>.

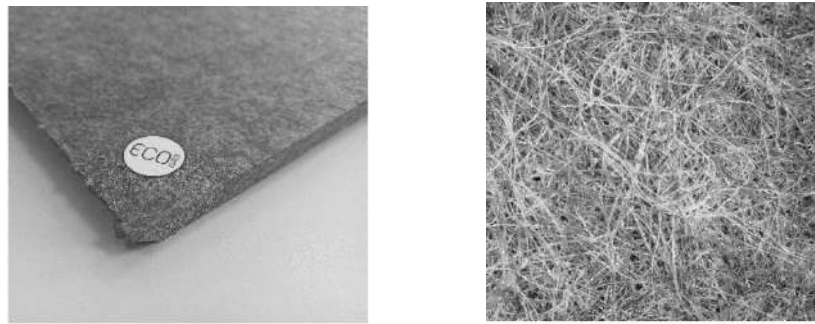


Figure 2: Eco-friendly PET panel: (Left) sample of the fabricated material and (Right) microstructure image obtained by SEM (Scanning Electron Microscope).

First, both the sound absorption and thermal performance of the fabricated panels were assessed following the standardized procedures described in ISO 11654 (ISO 11654) and BSEN12667:2001 (BSEN12667:2001), respectively, the results showing that these guarantee both an excellent acoustic and thermal comfort, with weighed sound absorption coefficients of 0.95 (class A) for a plenum arrangement, thermal conductivity values below 0.04 W/mK, and thermal resistance above 0.6 m²K/W, thus providing an excellent thermos-acoustic insulation.

In addition to its excellent thermos-acoustic properties, the resulting panel is resistant to fire, moisture, and microorganisms. Another key feature is that the panels are VOC certified, as assessed according to ISO 16000-6 (ISO 16000-6), so there is no need to worry about volatile organic compound emissions into the air, which is of great importance for guaranteeing air quality for its use in healthcare spaces. As for the maintenance, given that the PET material does not accumulate any type of fungus or bacteria (assessed following the procedure described in the ASTM G21-15 (ASTM G21-15)), it becomes much more occasional and can be reduced to dust or stain removal using conventional feather dusters/vacuum or alcohol-based cleaners, respectively. Finally, to extend the use of these panels to green buildings, more than 20 international certifications (LEED, BREEAM, etc.) were also accredited. To sum up, the proposed solution was not only shown to be comparable to conventional insulation systems used in buildings both in terms of thermal and acoustic performance (class A), but also yields antifungal properties and low VOC emission, which makes it suitable for its adoption in a broad range of healthcare environments, as it will be shown next.

Case Study: Childcare Room

One of the first actions was to set up a paediatric ward at the Hospital Universitario La Paz, one of the major hospitals in Spain. Specifically, the case study consisted of a childcare playroom in the Department of Paediatric Oncology, whose plan view, rendered view, and general view are depicted in Figure 3. Several layers of PET panels were installed perpendicular to the indoor ceiling using easy mounting glue, the acoustic treatment showing a 90% reduction in the average reverberation time values and a significant increase in the speech intelligibility parameters⁵.

⁵David del Rosario-Gilabert et al., “Eco-friendly and Biocompatible Material.”

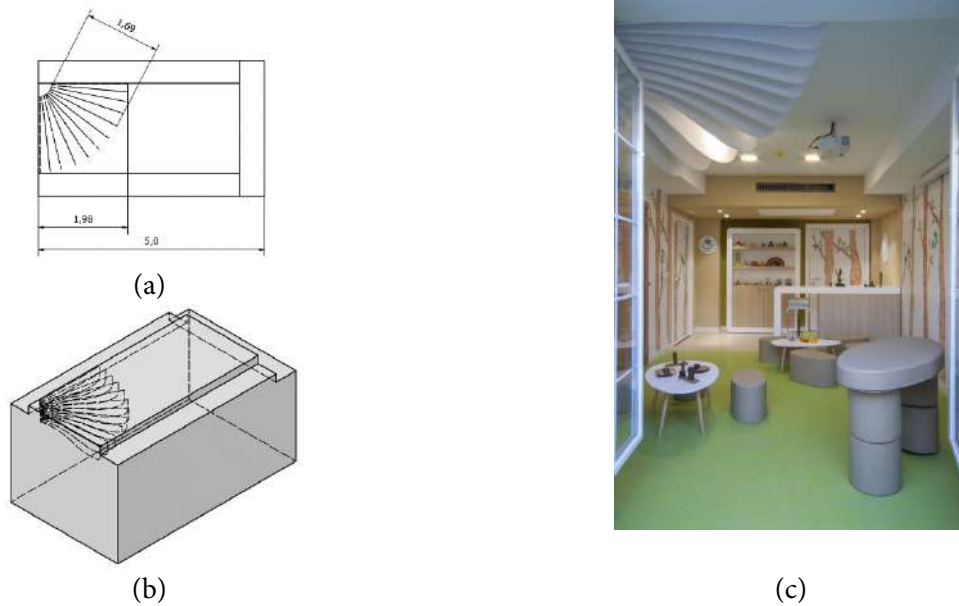


Figure 3: Case study of eco-friendly PET panels in a childcare playroom at the Hospital Universitario la Paz (Spain): (a) plan view, (b) rendered view, and (c) general view.

On the other hand, the design capabilities for sizing, shaping, and colouring make it very versatile and applicable to additional spaces such as reception halls or dining rooms (see some examples in Figure 4). In fact, the robust installation design features of these panels (e.g., tongue and groove) yield high durability and therefore a long service life while still being aesthetically attractive compared to conventional ones in terms of appearance.



Figure 4: Application of sound-absorbing PET panels in other scenarios: hall (left) and dining room (right).

Conclusions and Ongoing Research

In summary, the recycled and biocompatible acoustic material developed presents excellent features for its application in healthcare environments, including:

- Excellent sound absorption performance (class A).
- High thermal resistance and low thermal conductivity.
- Antifungal and moisture resistance.
- Low VOC emissions.
- Long-term durability.
- Aesthetic design capabilities.

In addition to the above features, it also shows promising perspectives for additional purposes in healthcare scenarios such as Intensive Care Units⁶ or incubators for cell dynamic viability assessment⁷, which constitute some of the ongoing research lines.

Acknowledgements

Special thanks to ECOCero Ltd. (material data and sample preparation) and D. Pascual Martínez Peinado from the University of Alicante for helping with the SEM images.

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⁶Jeanette Vreman et al., “The Effectiveness of the Interventions to Reduce Sound Levels in the ICU: A Systematic Review,” *Critical Care Explorations* 5, no. 4 (2023): e0885. <https://pubmed.ncbi.nlm.nih.gov/36998528/>.

⁷David del Rosario-Gilabert et al., “Eco-friendly and Biocompatible Material.”

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Chapter 45

Beyond the Object: Product and Furniture Design as Critical and Social Practice

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Abstract

In recent years, the field of design has faced a growing set of challenges. We present a series of student-led case studies examining how interdisciplinary and socially engaged design pedagogies can expand the role of the designer. Set within a multicultural studio context, students are encouraged to approach design as a critical and collaborative form of enquiry, foregrounding contextual awareness, positioning making as a vehicle for social awareness. Case studies reveal projects that develop critical design sensitivities, exploring the minutiae of everyday interactions through multimodal data collection and qualitative analysis. Situated examination of lived experiences and a re-evaluation of how artefacts might represent identity, culture, and technological values through function, materiality, and social meaning. It is understood that design should solve problems by drawing upon diverse methods and perspectives. High school programmes introduce social awareness, though they often lack the capacity to develop skills. STEM has increased emphasis on technical skills without integrating socio-cultural reflection¹. Pedagogical programmes presenting diverse approaches, systems, and contexts equip undergraduates with tools to generate new insights. This approach repositions the designer as facilitator, listener, and co-creator rather than as *auteur*.

Keywords: *Relational Design, Ethnomethodology, Situated Design, Social Engagement*

Introduction

Design education faces the challenge of equipping students with the ability to respond to social and ecological issues. Contemporary design requires sensitivity to relational and cultural contexts. The Product and Furniture Design course at UAL Chelsea follows a multidisciplinary trajectory shaped by an interdisciplinary team. Research and practice interests inform a curriculum that encourages critical reflection and socially responsive making, in line with Schön's concept of reflection-in-action².

The collaborative nature of course-making has produced pedagogical models that question notions of authorship. These models emphasise negotiation, iterative experimentation, and diverse perspectives. Home and international students bring prior educational, cultural, and disciplinary experiences. Students operate as makers, researchers, and facilitators. They generate knowledge through practice, using ethnographic methods to study everyday objects, revealing tacit social practices, which inform

¹"Design Economy: The Environmental and Social Value of Design," Design Council, accessed August 4, 2025, <https://www.designcouncil.org.uk/our-work/design-economy/#c8709>.

²Donald A. Schön, *The Reflective Practitioner: How Professionals Think in Action* (Abingdon, Oxon: Taylor and Francis, 1994), 46.

design interventions that challenge habitual behaviour or make cultural differences visible³. Critical engagement allows students to interrogate assumptions, identifying opportunities for socially responsive interventions³.

The course incorporates notional pathways: 'I, We, World', guiding students to explore personal, collaborative, and systemic design dimensions. This approach underpins three student-led case studies. *The Ecology of Action* engages local communities to co-design shared spaces, interrogating notions of participation and ownership. *The Social Object* examines how everyday artefacts acquire social and cultural meaning, revealing tacit skills and cross-cultural dialectics. *Rethinking Fans* explores material practices and cultural rituals through speculative design. These projects demonstrate how socially engaged and interdisciplinary pedagogy cultivates designers capable of critical, ethical, and contextually aware practice⁴.

Pedagogical Framework

The pedagogical model is explicitly interdisciplinary, encouraging students to engage with design as a relational, situated activity that considers social, cultural, and ecological contexts simultaneously. Methodologies drawn from ethnography and participatory research allow students to observe and interpret the dynamics of everyday life, cultural practices, and ecological impact. Students produce socially responsive, environmentally conscious, and critically informed design interventions.

Central to this approach is the repositioning of the designer from an isolated problem-solver to a facilitator, listener, and collaborator. Drawing on Freire's dialogic model of education, students co-construct knowledge through conversation, reflection, and mutual exchange while attending carefully to the perspectives of stakeholders and the environments in which their designs operate⁵. Shifting emphasis from delivering predetermined solutions to promoting a sensitivity to context and lived experiences.

Escobar's concept of relational and decolonial design provides a critical lens, examining dominant narratives and normative assumptions, encouraging students to create artefacts and interventions that acknowledge context, and multiple worldviews foregrounding interdependence⁶. Material experimentation is central, students consider how materials, form, function, and environmental impact intersect with social and cultural systems, how an object mediates interaction, expresses identity or responds to environmental constraints.

Case Studies

Building on this interdisciplinary and relational pedagogical framework, the following case studies illustrate how students apply participatory, ethnographic, and speculative methods in practice.

³Sarah Pink, *Doing Sensory Ethnography* (London: SAGE Publications Ltd, 2015), 141–144.

⁴Matt Malpass, *Critical Design in Context: History, Theory, and Practices* (Cambridge, Massachusetts: Bloomsbury Academic, 2017), 107–108; Anthony Dunne and Fiona Raby, *Speculative Everything* (The MIT Press, 2013), 105.

⁵Paulo Freire, *Pedagogy of the Oppressed*, trans. Myra Bergman Ramos (UK: Penguin Books, 2018).

⁶Arturo Escobar, *Designs for the Pluriverse: Radical Interdependence, Autonomy, and the Making of Worlds* (Durham: Duke University Press, 2018), 138.

Case Study 1: The Ecology of Action – Stockwell Co-design Project

The Ecology of Action is a hyper-local co-design initiative developed with a London community centre. The project engages residents by exploring community, identity, and shared spaces. Each year, the community centre sets a brief ensuring that work aligns with ongoing local needs while providing scope for creative experimentation.

Students approach by close observation of situated cultures and practices (Figure 1). This methodology encourages consideration of stakeholders' perspectives before the designer's individual ambitions. Students adjust their interventions in response to local priorities, enhancing social sensitivity and collaborative skills. Co-creation sessions encourage iterative dialogue, where students, staff, and community members develop solutions. Innovations include an equipped mobile workshop allowing construction of full-scale prototypes on site. Residents become closely involved as co-designers, contributing ideas, testing prototypes, and evaluating outcomes. This not only produces tangible objects but also generates insights into local identity and participatory methods. The project demonstrates how design can operate relationally as a negotiated practice responsive to the needs and knowledge of others⁷ (Figure 2).



Figure 1: Stockwell Park Community Centre selection day (Image: O. Callegaro, K. Sarkisyan, 2024).



Figure 2: Stockwell Park Community Centre Conversation Corner, Tipsey Railing (Image: O. Callegaro, 2024).

⁷Stockwell Community Centre, *Project Documentation* (London, UK: Chelsea College of Arts, 2024).

Case Study 2: The Social Object

The Social Object investigates everyday artefacts and their role in mediating social behaviour. Students explore how objects acquire meaning, reveal tacit skills, and reflect cultural norms and cross-cultural dialectics. They are equipped with flexible methods for observing and analysing objects, including video, note-taking, and observational drawing⁸.

Students undertake naturalistic experiments to understand objects from the perspective of others (Figure 3). The use of utensils, including knives, forks, and chopsticks, is analysed not simply as a perfunctory practice but as a cultural convention informing interaction. Students learn to interpret the relational and performative qualities of everyday tools (Figure 4).



Figure 3: Naturalistic experiment: Capturing 'Ordinary Affordances' (Image: J. Cleverly, 2022).



Figure 6: Sketch - people eat in circle



Figure 7: Sketch - People sharing food and feed each other



Figure 8: Sketch - how people eat while standing



Figure 4: Initial field studies, street food (Image: Y. Chen, 2024).

⁸Christian Heath and Jason Cleverly, "Discovering the Familiar: Exploring Everyday Practice in the Design of Tools and Artefacts," *International Journal of Art & Design Education* 45, no. 1 (2025): 77–93, <https://doi.org/10.1111/jade.12597>.

This approach proposes objects that embody social practices, facilitating interaction. The project reinforces the pedagogical aim of repositioning the designer as facilitator and observer capable of interpreting subtle social dynamics and translating these insights into design interventions⁹ (Figure 5).



Figure 5: Left: Objects that require the use of the water from the tap. Right: Tap disruption machine (Image: M. Gil, 2021).

Case study 3: Rethinking Fans

Rethinking Fans is a speculative project exploring environmental adaptation, material practice, function, and cultural ritual. Students examine the history, principles, and performance of fans, considering their use across diverse contexts. Experimentation with form, function, and materiality encourages exploration of how the fan might be reconfigured (Figure 6).

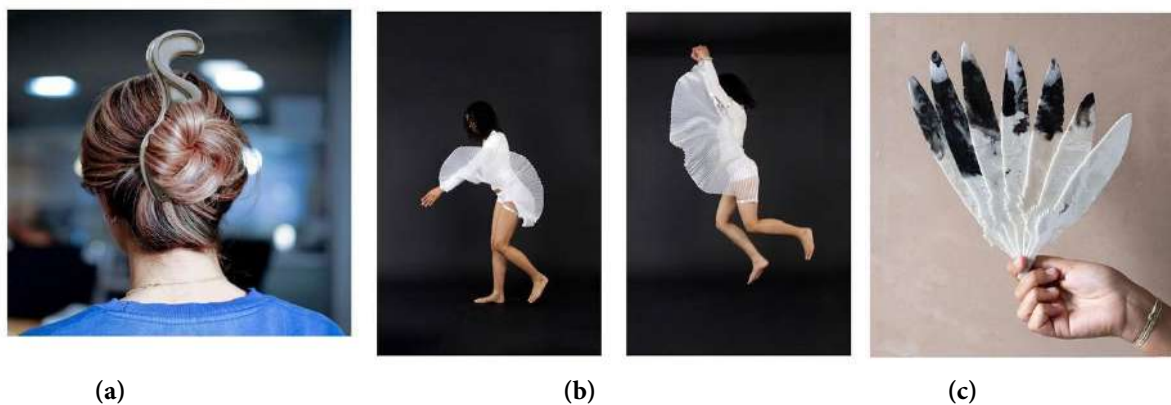


Figure 6: Rethinking fans (Images: J. Van Steen, 2022 (a); A. Digby, 2024 (b); and R. Hodges, 2022 (c)).

Through iterative prototyping, material testing, and reflection on ecological and social impact, students consider sustainability, health and well-being, fashion, communication, and cultural meaning in their proposals. The project emphasises risk-taking and inventiveness, and by connecting material practice with environmental and social considerations, it exemplifies a design pedagogy that is critically engaged, experimental and responsive to complex, real-world systems (Figure 7).

⁹Heath and Cleverly, “*Discovering the Familiar*,” 77–93.



Figure 7: Fan concept (Image: Sara Bshennaty, 2022).

Case Studies: Summary

These case studies show how socially engaged and interdisciplinary pedagogy shapes practice by cultivating designers who are critically reflective, contextually aware, and able to navigate relational, cultural, and ecological systems. Each project prioritises collaboration with communities, artefacts, and environments, positioning the designer as facilitator, observer, and co-creator rather than a detached problem-solver.

Conceptually, the studies highlight the relational nature of design, showing how objects mediate social practice, how participatory processes reveal local knowledge and identity and how speculative approaches produce new understandings of material and ecological systems. Methodologically, the projects demonstrate iterative reflexive practice. These methods produce critically informed, responsive, socially meaningful artefacts. Collectively, the case studies illustrate a pedagogical approach connecting theory and practice. Showing how design can develop practitioners capable of addressing nuanced, interconnected challenges.

Analysis and Insights

Case studies illustrate that design outcomes are not solely the result of material practice but equally shaped by relational processes embedded within broader social, cultural, and ecological contexts. Students begin to reconceptualise design not as an isolated act of problem-solving, but as a dialogic and situated practice shaped through collaboration, listening, and critical reflection. This repositions design as an inherently relational process responsive to context and attuned to multiple perspectives.

The model draws upon interdisciplinary frameworks from sociology, ecology, and critical theory. These frameworks encourage students to treat prototypes as research artefacts rather than as resolved solutions. Prototyping becomes a method of enquiry wherein the act of making elicits dialogue, revealing tacit knowledge to explore emergent possibilities. Material experimentation extends beyond form or function, a critical tool for understanding the systems in which design is situated.

The role of educators is also reframed. Rather than being solely instructors of technical competence, educators act as facilitators of enquiry, supporting collaborative learning, promoting reflexive engagement. Pedagogy becomes speculative in nature, offering a discursive space in which students and staff collectively interrogate assumptions underpinning design practices and experiment with alternative approaches. This emphasis on open-ended exploration encourages the capacity for critical awareness and adaptability, essential for navigating contemporary challenges.

Nevertheless, certain structural tensions exist. The ethos of open-ended enquiry can sit uneasily alongside the practicalities of the curriculum, which require clear outcomes and measurable progress. Risk-taking and experimental practices may be constrained by assessment frameworks that prioritise certainty and replicability. Similarly, while community collaborations offer significant pedagogical value, they are often limited by non-alignment with academic infrastructures. These challenges highlight the need for ongoing negotiation between institutional accountability and the imperative for experimental, socially responsive practice.

Conclusion

The pedagogical approach outlined here demonstrates the capacity of design education to address complex and interconnected local and global challenges. Ecological systems are conceptualised as frameworks that inform both the methodology and pedagogy of design education and position contextual awareness as integral to cultivating practices attuned to interdependence, systemic complexity, and ethics within socio-environmental contexts. Interdisciplinary frameworks encourage experimentation, approaching prototypes as tools for enquiry rather than resolved solutions. Teaching is reframed as a speculative and exploratory qualitative practice.

Of wider significance is the potential to influence practice beyond individual programmes. Integrating these methods within institutional structures might embed socially engaged and contextually aware approaches across curricula. Strengthening collaborations with communities, policymakers and other stakeholders increases the societal relevance of student practice. Sustaining institutional support for experimentation is essential, safeguarding the conditions required for risk-taking, critical thinking and reflexivity.

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Chapter 46

Prototype of the Sustainable Tourism Promotion Model Based on Technology 4.0 in Post-conflict Regions. Case Study: La Palma and Yacopí (Colombia)

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Abstract

The creation of sustainable cities and smart territories is an initiative that has been gaining importance in recent years. The prototype presented in this document is the result of a project entitled 'Development of a Model for Sustainable Tourism Promotion using Technology 4.0 in the municipalities of La Palma and Yacopí in the department of Cundinamarca', which aimed to develop a Model for Sustainable Tourism Promotion using Technology 4.0 in post-conflict regions through the application of immersive technologies. To this end, three pilot phases were developed, involving the community of the municipalities of La Palma and Yacopí (Cundinamarca, Colombia) in the survey of tourism offerings and the creation of a Sustainable Tourism Promotion Model, which facilitated the incorporation of technological elements for the recognition of the territory. The prototype created is an integrative model of the dimensions of sustainability, making it a process that can be applied in other territories. Finally, the importance of the project for territorial development, sustainable local promotion, and community-centred social innovation is highlighted, emphasising the value of collaborative work with local communities, tourism sector actors, and public authorities as a fundamental condition for ensuring its capacity to promote the economic, social, and cultural development of the regions.

Keywords: *Sustainable Tourism, Model, Technology, Community, Development*

Introduction

Tourism is one of the economic activities that contributes to regional development¹, promotes recognition of territories, their culture and traditions, and facilitates the creation of businesses in the regions.

¹Mehdi Nooripoor et al., "The Role of Tourism in Rural Development: Evidence from Iran," *GeoJournal* 84, no. 4 (2021): 1705–19, <https://www.jstor.org/stable/48754283>.

The World Tourism Organisation (UNWTO) states that tourism leads to increased Gross Domestic Product (GDP), job opportunities, higher incomes, and, as a result, increased demand for products and services².

However, in order to respond to new global trends and prevent damage to regions as a result of tourism activity³, territories are facing a variety of situations that are leading them to propose revitalisation strategies⁴ that incorporate elements related to sustainable tourism from social, environmental and economic dimensions and integrate innovative processes that emerge through research.

When regions have been victims of armed conflict, the challenges are even greater⁵. This is due to the need to incorporate tourism promotion strategies that highlight their social, cultural, historical, environmental, and economic benefits and characteristics⁶, while seeking to mitigate the negative image that may persist about these territories.

This document presents the results obtained from the Development of a Sustainable Tourism Promotion Model based on Technology 4.0 in post-conflict regions, from which a prototype for the recognition and development of territories has emerged. To this end, the study is based on the initiative proposed in 2021 within the framework of Call 13 of the General Royalties System, which was developed between 2022 and 2024 by the Secretariat of Science, Technology and Innovation of the Government of Cundinamarca and the Los Libertadores University Foundation, with the aim of increasing mechanisms for the promotion of sustainable tourism through innovation and technology in regions that have been so affected by violence: the case of the municipalities of La Palma and Yacopí.

In this regard, the prototype identifies strategies to promote tourism by implementing technological tools and incorporating augmented and virtual reality elements into the processes. These mechanisms favour the recognition, symbolic reconstruction and re-signification of the territory.

Results and Discussion

In various regions of the world, violence has left deep scars, generating negative consequences in economic, social, and environmental spheres. Colombia is one of the countries that have been victims

²"*Tourism and Travel-related Services*," World Trade Organization, accessed August 13, 2025, https://www.wto.org/english/tratop_e/serv_e/tourism_e/tourism_e.htm; Johan Ricardo Alonso Rodríguez, "El turismo como motor de crecimiento económico en Colombia (2000-2019): Tourism as an engine of economic growth in Colombia (2000-2019)," *Revista Internacional de Turismo, Empresa y Territorio* 6, no. 1 (2022): 57–83, <https://doi.org/10.21071/riturem.v6i1.14056>.

³Ulrika Persson-Fischer and Shuangqi Liu, "The Impact of a Global Crisis on Areas and Topics of Tourism Research," *Sustainability* 13, no. 2 (2021): 906, <https://doi.org/10.3390/su13020906>.

⁴Franz Tödting et al., "New Directions for RIS Studies and Policies in the Face of Grand Societal Challenges," *European Planning Studies* 30, no. 11 (2022): 2139–56, <https://doi.org/10.1080/09654313.2021.1951177>.

⁵Alexandra Huneus and Pablo Rueda Sáiz, "Territory As a Victim of Armed Conflict," *International Journal of Transitional Justice* 15, no. 1 (2021): 210–29, <https://doi.org/10.1093/ijtj/ijab002>.

⁶Zhizhang Zhao, "Tourism Development and Marketing Strategies in Emerging Markets," *Tourism Management and Technology Economy* 6, no. 7 (2023): 26–32, <http://dx.doi.org/10.23977/tmte.2023.060704>.

of these events for more than 60 years. Cundinamarca, a department with 116 municipalities spread across 15 provinces, possesses a wealth of tourist attractions and biodiversity. This presents a strategic opportunity to develop initiatives that promote tourism and support the region's economic growth. However, some of its municipalities have been affected by situations of violence generated by illegal groups. This is the case of La Palma and Yacopí, two territories located in the Province of Rionegro, which, despite their natural, cultural, social, and economic resources, were affected by violent acts that limited their development.

This situation has led to the need for initiatives that promote responsible recognition of the territory. Therefore, in 2021, as part of Call No. 13 of the General Royalties System, a project was proposed titled: 'Development of a Model for Sustainable Tourism Promotion using Technology 4.0 in the municipalities of La Palma and Yacopí, in Cundinamarca.' This project has helped strengthen sustainable, responsible, and inclusive tourism, emphasizing that activities in this sector become central to actions related to sustainable development. It involves the community and incorporates Industry 4.0 technologies, enhancing the visitor experience, promoting territory recognition, and facilitating the dissemination of activities.

These increasingly accessible technologies have proven their effectiveness in areas such as education, culture, and tourism promotion through immersive content and interactive experiences. In the case of the municipalities of La Palma and Yacopí, their implementation seeks not only to raise the profile of existing tourism offerings but also to contribute to processes of historical memory, social appropriation of the territory, and local economic reactivation.

Likewise, the development of different phases that gave rise to the first model of sustainable tourism promotion, which can be replicated across regions, stands out. Its results represent a commitment to the community's economic development, allowing the articulation of the different actors that are part of the country's productive ecosystem. This has led to a prototype that serves as an integrative mechanism for generating actions to recognise the territory, develop good tourism practices, manage sustainability-related processes, and contribute to the region's growth.

This has given rise to a prototype conceived as an integrating mechanism, aimed at generating actions for the recognition of the territory, promoting good practices in tourism, strengthening the management of processes related to sustainability, and contributing to the growth of the region.

Actions Taken to Develop the Prototype

The project entitled 'Development of a Sustainable Tourism Promotion Model based on Technology 4.0 in the municipalities of La Palma and Yacopí in the department of Cundinamarca' was developed from 2022 onwards by the Secretariat of Science, Technology and Innovation of the Government of Cundinamarca and the Los Libertadores University Foundation in three stages, which were fundamental for the creation of the integrative prototype:

Stage 1. Characterisation of tourism products in the municipalities of La Palma and Yacopí

The characterisation of tourist attractions was carried out according to the methodology guide for the preparation of the inventory of tourist attractions of the Colombian Vice-Ministry of Tourism. This

process was supported and participated in by the municipal councils of La Palma and Yacopí, tourism stakeholders and operators, and the community.

In this stage, the tourist products of the municipalities of La Palma and Yacopí were identified.

- Identify natural, tangible, and intangible cultural tourist attractions
- Identify tourist facilities
- Identify support infrastructure
- Identify superstructure

Stage 2. Creation of spaces for citizen participation in the co-creation of the Sustainable Tourism Promotion Model design

During this process, various activities were carried out to raise awareness of the importance of tourism. These included organising round tables with the community, stakeholders, and operators in the sector, as well as with municipal officials. These sessions yielded valuable material that served as input for the formulation of the sustainable tourism promotion model.



Figure 1: Activities carried out with the community.

In addition, the project contributed to local empowerment, recognising the importance of caring for the territory in relation to the tourist activities generated once the region's tourist attractions, customs, culture, and economy have been promoted. As a result of territorial cohesion, the Association of Sustainable Tourism for La Palma (ASOTURISPAL) and the La Ruta Minera de Yacopí Tourism Association were created.

Stage 3. Development of an information management tool to promote the Sustainable Tourism Promotion Model

Based on the information obtained, a prototype of the Sustainable Tourism Promotion Model was created, from which two websites and two apps (one for each municipality) were generated, incorporating elements of augmented and virtual reality in order to disseminate information about the municipalities: their natural attractions, gastronomic offerings, places of interest, tourist services, service providers, existing service networks, and relevant information on sustainability.

The web pages compile information that allows tourism service providers and the community to highlight the benefits of their municipality and promote and publicise their territory. At the same time, they are an essential source of information for visitors, who can learn about the municipalities' characteristics and attractions before their visit. The web pages feature videos of the territory and testimonials from the municipality's inhabitants.

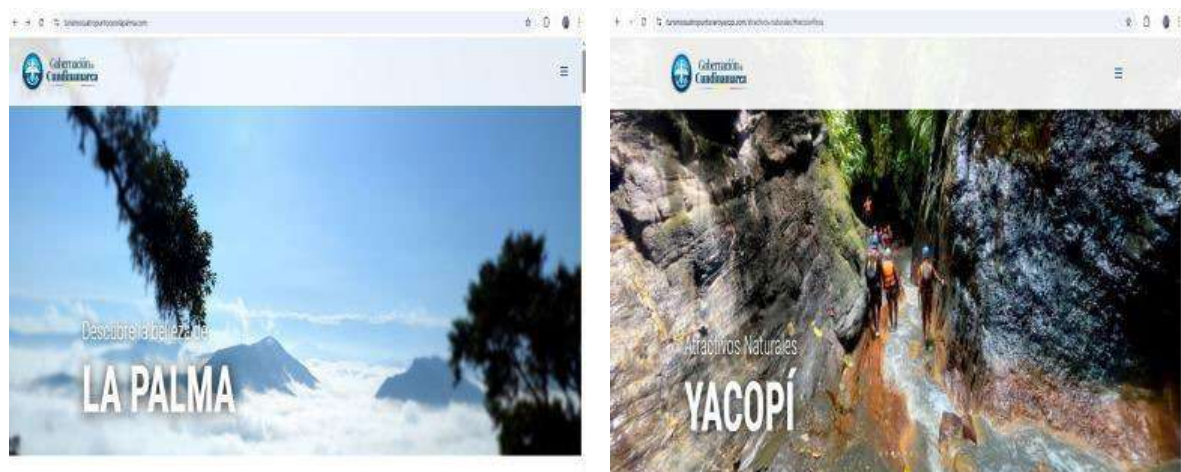


Figure 2: Website of the municipalities of La Palma and Yacopí (Sources: Website of the municipality of La Palma: <https://turismocuatro-puntocerolapalma.com/> and Website of the municipality of Yacopí: <https://turismocuatro-puntoceroyacopi.com/>).

The use of technologies such as augmented and virtual reality has become established as a strategic tool for highlighting tourist attractions, as well as the physical, cultural, and economic elements that add value to municipalities. These technologies allow for an immersive representation of the rich heritage of these territories, projecting them as destinations where sustainable tourism emerges as a key driver for boosting the local economy.

Therefore, the prototype created integrates the Sustainable Tourism Promotion Model, as well as the development and articulation of a website and an app that provides information about the territory.

Furthermore, the use of the Prototype Sustainable Tourism Promotion Model generates positive social and environmental impacts by promoting the region with a focus on conserving natural and cultural resources. These tools not only promote responsible practices aimed at caring for the environment⁷ but

⁷Williya Achmad and Yulianah Yulianah, "Corporate Social Responsibility of the Hospitality Industry in Realizing Sustainable Tourism Development," *Enrichment: Journal of Management* 12, no. 2 (2022): 1610–16, <https://doi.org/10.35335/enrichment.v12i2.447>.

also strengthen territorial identity and favour the preservation of local heritage, positioning tourism as a comprehensive strategy for sustainable development⁸.



Figure 3: Augmented and virtual reality objects in the municipalities of La Palma and Yacopí.

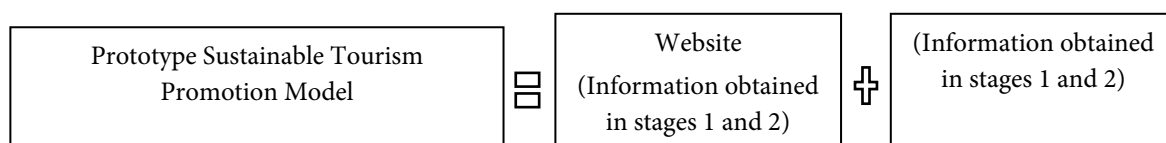


Figure 4: Diagram of the Prototype Model for Sustainable Tourism Promotion.

⁸Elisa Panzera, *Cultural Heritage and Territorial Identity* (Springer International Publishing, 2022), pp. 21

Conclusion

The creation of a Sustainable Tourism Promotion Model allows for the participation of communities, tour operators, national and local authorities, and strengthens the planning and governance of actions established for the promotion of tourism in the regions.

When territories have been affected by violence, strategies can be developed that combine innovative elements and technological development, facilitating community integration, the identification of tourist attractions, and the promotion of cultural and heritage wealth.

The creation of a prototype that articulates social, environmental, economic, and technological development in the regions facilitates a smart, scalable, and sustainable digital promotion strategy. It also allows operators to design plans tailored to customer needs and improve the customer experience.

It is worth noting that this initiative is a pilot project with the potential to be replicated in other contexts worldwide. It can also be enriched by incorporating new elements and information through georeferencing and artificial intelligence, as determined by the researchers involved in this initiative. This would constitute a second phase of the project and would represent a significant contribution to the territories' economies.

Acknowledgements

The support and articulated work carried out between the Secretariat of Science, Technology and Innovation of the Government of Cundinamarca and the Los Libertadores University Foundation is recognised within the framework of the SGR project called 'Development of a Sustainable Tourism Promotion Model based on Technology 4.0 in the municipalities of La Palma and Yacopi in the Department of Cundinamarca'.

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Chapter 47

Study of Intergenerational Craft and Revival in Himalayan Communities

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Abstract

Uttarakhand, a culturally rich and geographically diverse state in the Indian Himalayan region, has a longstanding tradition of wool-based handicrafts such as handknitting. These practices are not only utilitarian but also serve as a medium for transmitting cultural heritage across generations. This paper explores the role of handknitting as a conduit for intergenerational bonding and the preservation of traditional knowledge within Himalayan communities. Drawing on qualitative data collected through interviews with artisans and community members, the study highlights how the act of craft-making fosters deep interpersonal connections. These shared creative experiences strengthen familial ties and offer a sense of identity and belonging, particularly between elders and younger generations. Despite this, the tradition faces critical challenges in the context of modern consumer culture. The increasing availability of inexpensive, mass-produced garments has marginalised handmade crafts, diminishing their market appeal and limiting their visibility. There is also a marked decline in the number of young people engaging with these practices, posing a serious threat to their continuity. The diminishing interest among youth is identified as one of the most pressing concerns for the sustainability of these cultural expressions. This paper examines both the underlying factors contributing to this decline and its broader cultural implications. It also sheds light on current revival efforts, including community initiatives, institutional support, and evolving strategies aimed at re-engaging younger generations with their craft heritage.

Keywords: *Uttarakhand, Intergenerational, Community, Craft, Revival, Cultural Expressions*

Introduction

Uttarakhand State was carved out of the state of Uttar Pradesh on 9th November 2000. It is divided into two broad regions—Garhwal and Kumaon. The state is comprised of 13 districts, namely, Chamoli, Pauri, Tehri, Uttarkashi, Dehradun, Haridwar, and Rudrapur in the Garhwal region and Nainital, Almora, Pithoragarh, Udham Singh Nagar, Champawat, and Bageshwar in the Kumaon region. Of these 13 districts, four (Nainital, Haridwar, Dehradun, and Udham Singh Nagar) have large areas in the plains, whereas the other nine districts comprise the state's hill region. In the hill regions of Uttarakhand, it is common to see women seated on the verandas of their homes in the morning sunlight, engaged in activities such as knitting, spinning, and other crafts. These quotidian interactions extend beyond utilitarian production, serving as important sites of sociality and community building. The shared practice of craft not only sustains traditional knowledge systems but also fosters collective bonds among women, reinforcing networks of support within the community. An important aspect of craft-making and transmitting culture is spending time together across generations and within the

community. Craft-making can also connect people with their roots and ancestors through inherited shared skills and craft objects¹. As scholars have noted, craftmaking functions as a vehicle for heritage transmission, with women seeking to “keep the family tradition alive”² or to “leave a legacy” for future generations³. The shared practice of craft not only sustains traditional knowledge systems but also fosters collective bonds among women, reinforcing networks of support within the community⁴.

Discussion

Field observations in Dunda village (Uttarkashi, Uttarakhand) highlight the persistence of wool-based crafts, particularly knitting, among older women who gather in the morning sun to practice and socialise (Figure 1). These scenes embody both the continuity of cultural practices and the role of craft as a community-building activity. However, they also make visible a generational gap: while elderly women remain active, younger women are rarely seen participating. This reflects a wider trend in India, where inexpensive, mass-produced garments and shifting aspirations have undermined the appeal of traditional handicrafts, leading to a marked decline in participation among younger people⁵.



Figure 1: Women knitting in a group, basking in the sun at Dunda, Uttarkashi, Uttarakhand.

¹Ute Schönplugg, “Introduction: Cultural Transmission— A Multidisciplinary Research Field: Cultural Transmission— A Multidisciplinary Research Field,” *Journal of Cross-Cultural Psychology* 32, no. 2 (2001): 131–34, <https://doi.org/10.1177/0022022101032002001>.

²Joyce Starr Johnson and Laurel E. Wilson, “It Says You Really Care”: Motivational Factors of Contemporary Female Handcrafters,” *Clothing and Textiles Research Journal* 23, no. 2 (2005): 115–30, <https://doi.org/10.1177/0887302X0502300205>.

³Kathleen W. Piercy and Cheryl Cheek, “Tending and Befriending: The Intertwined Relationships of Quilters,” *Journal of Women & Aging* 16 no. 1–2 (2004): 17–33, https://doi.org/10.1300/J074v16n01_03.

⁴Riikka Myllys, “Nowhere and Everywhere: Everyday Religion in the Intergenerational Transmission of Craft Making,” *Temenos - Nordic Journal of Comparative Religion* 56, no. 1 (2020): 53–74; Johnson and Wilson, “It Says You Really Care,” 115–30.

⁵Surabhi Mittal et al., “Development Strategy for the Hill Districts of Uttarakhand,” Working Paper No. 217 (New Delhi: Indian Council for Research on International Economic Relations (ICRIER), 2008), <https://ideas.repec.org/p/ind/icrier/217.html>.

The continued relevance of these practices is closely tied to broader questions about the value of handmade objects. Smith notes that handmade artefacts possess a ‘soul’, reflecting the spirit of the maker and offering consumers a sense of personal identity distinct from mass-produced goods⁶. Yet, rapid urbanisation, mechanisation, and changing consumer preferences have marginalised artisans, a challenge made more acute by the COVID-19 pandemic, which disrupted supply chains and worsened economic vulnerabilities. At the same time, scholars emphasise that each handmade motif carries symbolic meaning and ecological awareness, underscoring the cultural stakes of preserving such traditions.

Youth Disinterest

The decline in participation is most evident among younger generations. Interviews and secondary research reveal that economic, educational, and social factors shape this disengagement (see Table 1).

Table 1: Key reasons and explanations for the decline in participation among younger generations.

Sr. No.	Reasons	Explanation
1	Economic/market pressures	Many youths have seen parents struggle for fair prices or stable income, making other trades more appealing ⁷ .
2	Educational/career pathways	Formal schooling encourages aspirations for urban or white-collar jobs, pushing youth away from craft practices ⁸ .
3	Social stigma and identity	Certain crafts carry caste associations or are perceived as ‘old-fashioned’, leading to disengagement ⁹ .
4	Modern preferences/lifestyle	Ready-made knitwear and modern fashion trends reduce demand for handcrafted goods, making them seem outdated ¹⁰ .

⁶Paul J. Smith, ed. *Objects for Use: Handmade by Design* (New York: Harry N. Abrams in association with the American Craft Museum, 2001), pp.; Akansha Dobriyal and Swati Sarkar, “A Review of Uttarakhand’s Craftsmanship in Natural Textiles and Traditional Weaving,” *Tuijin Jishu/Journal of Propulsion Technology* 45, no. 4 (2017): 1001–55,

https://www.researchgate.net/publication/392848346_A_Review_of_Uttarakhand's_Craftsmanship_in_Natural_Textiles_and_Traditional_Weaving.

⁷Dasra, *Crafting a Livelihood: Building Sustainability for Indian Artisans* (Mumbai: Dasra, 2013), <https://www.dasra.org/pdf/resources/Crafting%20a%20Livelihood%20-%20Building%20Sustainability%20for%20Indian%20Artisans.pdf>

⁸LiveMint, “Is the Indian Karigar Ageing?,” Mint, June 2023.

⁹LiveMint, “Is the Indian Karigar Ageing?”

¹⁰Uttarakhand Handloom and Handicraft Development Council (UHHDC), District Units and Programs (Government of Uttarakhand, n.d.), https://doi.uk.gov.in/mysite/about_uhhdc.

This generational shift highlights an urgent need for adaptive strategies to re-engage youth, whether through integrating craft education into schools, ensuring artisans earn sustainable wages, or reframing crafts as contemporary and aspirational practices.

Revival Efforts

Despite these challenges, several initiatives aim to revive crafts in Uttarakhand. The Uttarakhand Handloom and Handicraft Development Council (UHHDC) has established district units to provide training, organise fairs, and create producer–buyer linkages¹¹. NGOs like Avani in Kumaon have introduced design interventions and established cooperatives such as *EarthCraft*, enabling artisans to experiment with natural dyes and sustainable practices¹². Similarly, Rishikesh Natural Fiber Handicrafts has conducted government-sponsored training programs in Bhimal fibre weaving and design¹³. Design-led enterprises like *Peoli* in Almora employ local knitters, pay them higher wages, and adapt traditional techniques for modern markets¹⁴.

At the national level, programs under the Development Commissioner (Handicrafts)—including the National Handicrafts Development Programme (NHDP)—promote training, design support, and recognition for artisans¹⁵. Together, these initiatives illustrate how heritage preservation can intersect with livelihood development, offering a model of revival that balances tradition and innovation.

Conclusion

This study, inspired by observations in Dunda village, underscores the fragile continuity of Uttarakhand's craft traditions. While wool-based practices like knitting remain central to older women's daily lives and community bonds, youth disengagement and market pressures pose existential challenges. Revival efforts in Uttarakhand—spanning government councils, NGOs, cooperatives, and design enterprises—demonstrate that culturally grounded crafts can be revitalised when linked to economic sustainability and contemporary relevance.

The findings resonate beyond Uttarakhand. Similar patterns of generational decline are evident in other Indian craft communities, where modernisation and mass production erode traditional skills. By framing crafts as aspirational, ensuring dignified livelihoods, and embedding them within broader cultural and economic strategies, India can preserve its diverse heritage. As UNESCO emphasises,

¹¹Avani, Sustainable Livelihoods through Craft, Avani Earthcraft Cooperative, <https://avani-kumaon.org/>.

¹²Rishikesh Natural Fiber Handicrafts Producer Company, Bhimal Fiber Training Program (Ministry of Textiles, Government of India, 2023), <https://rishikeshnaturalhandicrafts.com/index.html>.

¹³“About Us,” Peoli, https://www.peoli.in/pages/about-us?srltid=AfmBOopRvNVkWRvYYLGdtnjyC6dnyzaHg413wPm_wX8yjniWvBcbEh7E.

¹⁴Ministry of Textiles, Government of India, National Handicraft Development Programme (NHDP), <https://www.india.gov.in/information-national-handicrafts-development-programme-nhdp?page=1>.

¹⁵UNESCO, “Safeguarding West Bengal's Intangible Cultural Heritage,” UNESCO, 2025, <https://www.unesco.org/en/articles/safeguarding-west-bengals-intangible-cultural-heritage#:~:text=Through%20its%20initiatives%2C%20the%20Rural,Nations%202030%20Sustainable%20Development%20Agenda>.

safeguarding intangible cultural heritage requires intergenerational participation and community ownership¹⁶. Ultimately, the Uttarakhand experience illustrates both the risks of cultural erosion and the possibilities of revival, offering lessons for sustaining traditional crafts across the subcontinent.

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¹⁶UNESCO, "Convention for the Safeguarding of the Intangible Cultural Heritage," *UNESCO*, 2003, <https://ich.unesco.org/en/convention>.

- Rishikesh Natural Fiber Handicrafts Producer Company. 2023. Bhimal Fiber Training Program. Ministry of Textiles, Government of India. <https://rishikeshnaturalhandicrafts.com/index.html>.
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Chapter 48

Agentic AI for Sustainable Behaviour: A Coaching Framework and Workflow

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Abstract

Addressing the climate crisis requires individuals to adopt and maintain multiple low-carbon behaviours across diverse aspects of everyday life. Traditional behavioural interventions, although effective in specific contexts, often lack the scope and longevity needed for transformative lifestyle change. This article proposes a novel approach: an agentic AI workflow designed to coach individuals towards sustainable behaviour by operating across key high-impact domains, including food, transport, energy, and consumption. Unlike conventional tools that offer static prompts, agentic AI systems demonstrate autonomy, adaptability, and goal-directed reasoning. They perceive user behaviour, diagnose psychological barriers, and dynamically tailor evidence-based interventions using behavioural science frameworks. The proposed system comprises 12 interdependent AI agents, each responsible for functions such as data collection, behavioural diagnostics, personalised coaching, and continuous evaluation. Together, they deliver an adaptive and context-aware coaching experience that supports behavioural change and maintenance over time. This agentic AI framework provides a scalable and personalised solution to help individuals reduce their carbon footprint and support a broader societal shift towards sustainability.

Keywords: *Sustainability, Transformation, Agentic AI, Behaviour, Intervention*

Introduction

Behavioural science has generated many interventions that can successfully encourage specific sustainable behaviours, from reducing meat consumption to recycling¹. However, such interventions are often context-specific and rarely add up to the scale of lifestyle transformation needed to meet climate goals². Achieving a sustainable society requires individuals to adopt multiple low-carbon practices across several areas of daily life and to sustain these changes over time³. To address this

¹Linda Steg, "Psychology of Climate Change," *Annual Review of Psychology* 74 (2023), <https://doi.org/10.1146/annurev-psych-032720-042905>.

²Lorraine Whitmarsh and Sam Hampton, "Are Radical Changes to Lifestyles Necessary for Mitigating Climate Change?," *Dialogues on Climate Change* 1, no. 1 (2024): 23–29, <https://doi.org/10.1177/29768659241293215>.

³Dario Krpan, "Agenda for Psychological and Behavioural Science of Transformative Behavioural Change," in *Behavioural Public Policy*, ed. Adam Oliver (Cambridge University Press, 2024), 1–26.

challenge, this article proposes an agentic AI workflow: a system designed to coach people toward comprehensive, long-term lifestyle change by guiding behaviour across high-impact domains (e.g., food, transport, energy, consumption) and suggesting low-carbon alternatives for high-emission activities.

What Agentic AI Is and How It Goes Beyond Traditional Interventions for Sustainable Behaviour

Agentic AI refers to artificial intelligence systems that do not merely respond to inputs but actively pursue complex goals with autonomy, adaptability, and self-directed reasoning⁴. Unlike conventional digital tools or nudges, which deliver static information or one-off behavioural prompts, agentic AI systems can perceive user behaviour across contexts, diagnose underlying psychological barriers, and dynamically select and adapt interventions based on behavioural science evidence⁵. This goes beyond traditional interventions that often rely on generic messages or isolated tactics, which can fail to sustain long-term change. By combining continuous learning, personalisation, and proactive problem-solving, agentic AI offers a powerful framework for helping individuals not only adopt but also maintain sustainable behaviours, making it particularly suited for addressing high-carbon lifestyle domains where lasting behavioural transformation is needed.

Agentic AI Workflow

The main idea that underpins the workflow is that high-carbon behaviours over which people have some control, and which they can therefore change, can be grouped into Domains 1-5 described in Table 1⁶. Therefore, by learning to adopt lower-carbon behaviours within those domains, individuals can reduce their carbon footprint. As indicated in Table 1 (Domain 6), it is also assumed that, in some cases, reducing undesirable behaviours (e.g., shopping less) is difficult unless individuals are offered a suitable alternative (e.g., reading). This idea is informed by research on smoking, which shows that quitting is more successful when a replacement behaviour is introduced⁷. Therefore, Domain 6 does not target behaviours that should be reduced or changed, instead, it focuses on providing suitable replacements.

⁴Deepak Bhaskar Acharya et al., “Agentic AI: Autonomous Intelligence for Complex Goals—A Comprehensive Survey,” *IEEE Access* 13 (2025): 18912–36, <https://doi.org/10.1109/ACCESS.2025.3532853>.

⁵Eric Yang et al., “From Barriers to Tactics: A Behavioral Science-Informed Agentic Workflow for Personalized Nutrition Coaching,” *arXiv Preprint arXiv:2410.14041* (2024).

⁶Christophe Lembregts and Romain Cadario, “Consumer-driven Climate Mitigation: Exploring Barriers and Solutions in Studying Higher Mitigation Potential Behaviors,” *International Journal of Research in Marketing* 41, no. 3 (2024): 513–28, <https://doi.org/10.1016/j.ijresmar.2024.04.001>.

⁷Patricia M. Goelz et al., “The Association between Changes in Alternative Reinforcers and Short-term Smoking Cessation,” *Drug and Alcohol Dependence* 138 (2014): 67–74, <https://doi.org/10.1016/j.drugalcdep.2014.02.007>.

Table 1: Key behaviour change domains for sustainable lifestyle transformation that inform the agentic AI workflow.

Domain	Description
1. Transport	Reducing reliance on high-carbon transport by shifting to lower-emission options such as public transport, cycling, walking, and more efficient travel modes.
2. Food	Lowering the carbon footprint of diets through more plant-based meals, less food waste, and choosing seasonal and locally produced foods.
3. Energy & Resources	Cutting unnecessary energy, water, and material use with efficiency measures, renewable energy choices, and correct recycling practices.
4. Consumption	Minimising high-impact purchases by buying less, choosing durable or second-hand products, and supporting circular, low-waste options.
5. Ethical Alignment	Aligning financial choices and consumer voice with sustainable providers, responsible investments, and ethical standards.
6. Leisure	Promoting enjoyable low-carbon activities and hobbies that can substitute for higher-impact pastimes while maintaining quality of life.

In a nutshell, the agentic AI system is designed to coach individuals to adopt more environmentally friendly lifestyles across Domains 1–5 (Table 1), while also helping them find suitable replacements for high-emission activities they previously enjoyed (Domain 6). More specifically, the agentic AI system needs to: (a) identify domains where individuals underperform, using data from sources such as self-reports, smartphones, and smart home devices; (b) determine the main behavioural barriers contributing to this underperformance; (c) propose targeted behavioural interventions that directly address these barriers, informed by behavioural science literature; (d) suggest appropriate low-carbon activities to replace high-emission behaviours individuals may wish to reduce; (e) continuously track and evaluate the effectiveness of interventions to improve outcomes; and (f) provide individuals with estimates of their carbon footprint to support awareness and monitor progress.

The proposed agentic workflow consists of 12 agents described in Table 2 that work together to achieve these goals. The system begins by collecting and processing relevant data from multiple sources (Data Collector Agent), which is then used to estimate the individual's carbon footprint (Carbon Counter Agent) and identify domains where performance is strong or where improvement is needed (Progress Monitor Agent), addressing goals (a) and (f). When underperformance is detected, the system identifies the underlying behavioural barriers that may be limiting progress (Barrier Finder Agent), fulfilling goal (b). These insights are passed to the appropriate domain-specific coach (e.g., Travel, Food, Energy, Consumption, and Ethical Alignment Domain Coaches), which selects tailored, evidence-based interventions to address the identified barriers (goal c). In parallel, the system also suggests low-carbon

alternatives for high-emission behaviours individuals may wish to reduce (Leisure Domain Coach Agent), addressing goal (d). These interventions are delivered using adaptive and personalised communication that fits the individual's motivations and context (Communicator Agent). Finally, the impact of these interventions is continuously monitored and used to refine future strategies (Evaluator Agent), thereby supporting goal (e). Together, this coordinated set of agents forms a dynamic, personalised coaching system designed to help individuals live more sustainably.

Table 2: Agents that constitute the workflow.

Agent	Description
1. Data Collector	Gathers and processes relevant data from multiple sources (e.g., smartphones, smart home devices, spending records) and stores it in a shared profile other agents can use.
2. Carbon Counter	Estimates the carbon impact of activities by combining data on travel, food, energy use, and purchases with emission factors, then shows a clear breakdown by area.
3. Progress Monitor	Highlights domains and activities where the individual is already performing well and points out domains where there is the greatest room for improvement.
4. Barrier Finder	Identifies the main behavioural barriers to sustainable action by drawing on behavioural science theories and frameworks, and passes this on to the domain-specific coaches.
5. Travel Domain Coach	Selects personalised, evidence-based interventions (e.g., goal setting, social comparisons) to encourage lower-carbon travel choices such as public transport, cycling, or walking.
6. Food Domain Coach	Uses tailored behavioural strategies to support shifts towards lower-carbon diets, reduce food waste, and promote sustainable shopping habits.
7. Energy Domain Coach	Provides context-specific interventions to reduce energy and water use at home, such as optimising heating or encouraging efficient appliances.
8. Consumption Domain Coach	Applies behavioural techniques to guide more sustainable consumption, including buying less, choosing durable or second-hand goods, and reducing packaging.
9. Ethical Alignment Coach	Delivers personalised interventions that align financial choices and consumer voice with sustainability values, responsible investments, and ethical standards.
10. Leisure Domain Coach	Suggests fulfilling, low-carbon leisure alternatives, chosen to fit the individual's motivations and lifestyle so that sustainable living remains enjoyable.

Table 2: Continued.

Agent	Description
11. Communicator	Delivers the interventions recommended by domain-specific coaches and presents them through adaptive, personalised communication.
12. Evaluator	Tracks the impact of interventions delivered by the Communicator agent and continuously improves the intervention strategy over time.

Practical Implementation and Conclusion

The proposed agentic AI system could be practically implemented as a multi-agent architecture using existing conversational AI platforms, large language models (LLMs), and behavioural data pipelines. Each agent described in Table 2 can be instantiated as a modular AI component with clearly defined roles and shared access to a user profile and data environment. For example, platforms such as Microsoft’s Semantic Kernel, Google’s Vertex AI, or open-source orchestration frameworks like Haystack allow for modular agent construction and dialogue management across tasks. Data collection can be achieved through permissioned integrations with smartphone sensors, smart home devices, and similar data sources commonly used in digital behaviour change interventions⁸. Personalised feedback and barrier-informed coaching can be powered by fine-tuned LLMs or rules-based classifiers trained on behavioural science frameworks, such as COM-B⁹. Evaluation and adaptive learning loops can be implemented using reinforcement learning or Bayesian policy optimisation techniques, allowing the system to update intervention strategies over time based on observed outcomes. Together, these technologies provide a practical pathway to deploy the agentic AI workflow as an intelligent digital coaching system for sustainable behaviour change.

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Chapter 49

Design for Change: Transformational Cross-cultural and Transdisciplinary Learning Experiences to Solve Global Healthcare Sustainability Challenges

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Abstract

As populations live longer and healthcare demands rise, building a sustainable and resilient healthcare system is urgent. Around the world, healthcare is under pressure—not just to treat more people, but to do so sustainably. However, what is often overlooked is the high environmental cost of modern healthcare systems, particularly through their carbon footprint and material waste. Globally, the healthcare sector contributes significantly to greenhouse gas emissions, comparable to large industries. In response to the challenges, this article presents an educational initiative centred on cross-cultural and multidisciplinary collaboration among undergraduate students in design and health sciences. Through immersive experiential learning and design sprints, students explore real-world healthcare sustainability challenges, generating context-sensitive, equitable, and environmentally responsible solutions. This model highlights the importance of integrating environmental stewardship, technological ethics, and inclusive design. The authors posit that a curriculum engaging undergraduate health and design students from diverse cultural backgrounds is essential for lasting change in healthcare systems.

Keywords: *Design Education, Health Education, Design Sprints, Experiential Learning, Sustainability, Problem-based Learning*

Introduction

According to *Harvard Medicine*, the global healthcare sector contributes between 4.4% and 5.2% of greenhouse gas emissions—comparable to or exceeding aviation¹. In Australia, healthcare accounts for approximately 7% of national carbon emissions, reaching 30% across the Asia-Pacific region². These emissions are linked to climate-sensitive health conditions, including respiratory and cardiovascular diseases and heat-related morbidities. Beyond emissions, material waste in healthcare presents a

¹Stephanie Dutchen, “Confronting Health Care’s Carbon Footprint,” *Harvard Medicine: Nature, Nurture*, 2023, <https://magazine.hms.harvard.edu/articles/confronting-health-cares-carbon-footprint>.

²Jeremy Chan, “Managing Asia’s Healthcare Waste and Emissions Remains Challenging Amid Increasing Climate Risks,” *Eco-Business*, 2024, <https://www.eco-business.com/news/managing-asias-healthcare-waste-and-emissions-remains-challenging-amid-increasing-climate-risks/>.

pressing challenge, with over 16 billion injections administered each year globally, using single-use plastics that contribute to biohazardous and environmental waste³. Healthcare sustainability is one of the most pressing challenges of the 21st century, as modern systems also generate significant environmental impacts through emissions, waste, and energy use. Technological advancements tend to concentrate in urban, high-income regions, leaving rural and marginalised populations at a disadvantage, highlighting the need for inclusive innovation strategies, particularly as digital health systems introduce additional environmental considerations across their lifecycle⁴, including the growing intersection between artificial intelligence, healthcare, and climate impacts⁵. The challenge lies not only in technological deployment but also in governance, regulation, and ethical stewardship to prevent digital exclusion and systemic discrimination. This urgency is further reinforced by global policy frameworks calling for climate-resilient and low-carbon healthcare systems⁶.

Although these challenges are often assumed to be addressed within health sciences, the required skill sets extend beyond this domain. Design processes are recognised for supporting sustainability, particularly in product design, and as evidenced by Papanek, designers have contributed to the sustainable development agenda since the 1970s⁷. In ‘Design for the Real World’, Papanek describes designers as agents of change capable of innovating products, services, and systems. He positions design beyond aesthetics, with its success measured by its ability to deliver meaningful, functional solutions within context. These theories underpin contemporary design education, emphasising the role of design in shaping worldviews, relationships, and empathy.

Globalisation and the transfer of ideas across cultural and political boundaries require an understanding of cross-cultural relationships. To achieve effective and sustainable healthcare innovation, global competencies are essential. As Jensen notes, organisations must consider cross-cultural collaboration to connect global and local knowledge and build shared innovation cultures⁸, reinforcing the need for globally aware practitioners⁹.

³World Health Organization, “Healthcare Waste,” WHO, 2024, <https://www.who.int/news-room/fact-sheets/detail/health-care-waste>.

⁴Yacine Hadjiat, “Framework for the Environmental Sustainability of Digital Health Systems,” *PLOS Digital Health* 2, no. 5 (2023): e0000268, <https://doi.org/10.1371/journal.pdig.0000268>.

⁵Daiju Ueda et al., “Climate Change and Artificial Intelligence in Healthcare: Review and Recommendations Towards a Sustainable Future,” *Diagnostic and Interventional Imaging* 105, no. 11 (2024): 453–59, <https://doi.org/10.1016/j.diii.2024.06.002>.

⁶COP28 UAE, *COP28 UAE Declaration on Climate and Health* (United Nations Framework Convention on Climate Change, 2023), <https://www.cop28.com/en/cop28-uae-declaration-on-climate-and-health>.

⁷Victor Papanek, *Design for the Real World: Human Ecology and Social Change* (Academy Chicago Publishers, 1971).

⁸Karina R. Jensen, “Global Innovation and Cross-Cultural Collaboration: The Influence of Organizational Mechanisms,” *Management International / International Management / Gestión Internacional* 19 (2015): 101.

⁹Lisa Scharoun et al., “Understanding Design Culture from East to West: A Transdisciplinary Approach to Teaching,” in *Contemporary Design Education in Australia: Creating Transdisciplinary Futures*, ed. Lisa Scharoun et al. (Intellect, 2023).

Providing students with learning experiences in significantly different cultural contexts enhances cultural intelligence¹⁰ by broadening perspectives and supporting global learning outcomes¹¹. The authors posit that these competencies can be developed through immersive experiential and problem-based learning (PBL), where cross-cultural and multidisciplinary design sprints enable students to address real-world healthcare sustainability challenges

Methods

Students addressing real-world problems in diverse cultural settings are pushed to transcend boundaries and create impactful solutions, with adaptation to cultural contexts fostering innovation¹². An experiential PBL methodology supports knowledge sharing and equal participation among individuals from diverse backgrounds.

PBL draws on complex real-world problems without single solutions, with group work enabling multiple perspectives and a more comprehensive investigative approach¹³, aligning with design thinking approaches to problem-setting and need-finding in complex contexts¹⁴. To support this, students engaged in pre-work and a symposium featuring global experts who provided a strong knowledge base. Through these activities, students were introduced to the UN Sustainable Development Goals 3, 11, and 8, forming a foundation for developing solutions addressing global healthcare challenges.

Experiential learning extends beyond the classroom and relies on the formation and reformation of ideas through immersion in unfamiliar environments that promote rapid shifts in perspective¹⁵.

Design sprints are intensive studio experiences, typically lasting 5 days or less, where teams ideate, prototype, and test solutions through guided design thinking processes, widely applied in healthcare to

¹⁰Lisa Scharoun et al., “Transforming Perspectives: Fostering Cross-Cultural and Transdisciplinary Competencies through Industry Engagement on Short-Term Study Tours,” in *Contemporary Design Education in Australia: Creating Transdisciplinary Futures*, ed. Lisa Scharoun et al. (Intellect, 2023).

¹¹Lisa Scharoun, “Short-Term Study Tours as a Driver for Increasing Domestic Student Mobility in Order to Generate Global Work-Ready Students and Cultural Exchange in Asia Pacific,” *Perspectives: Policy and Practice in Higher Education* 20, nos. 2–3 (2015): 83–90, <https://doi.org/10.1080/13603108.2015.1075917>.

¹²Marianella Chamorro-Koc and Lisa Scharoun, “Design Sprints, Designathons and Place-Based Learning in the Context of Real-World Health Problems,” *International Journal of Art and Design Education* 44, no. 3 (2025): 677–92, <https://doi.org/10.1111/jade.12578>.

¹³Gjoko Muratovski et al., “Approaching Global and Local Examples of Transdisciplinary Projects in the United States, Indonesia, China and Australia,” in *Contemporary Design Education in Australia: Creating Transdisciplinary Futures*, ed. Lisa Scharoun et al. (Intellect, 2023).

¹⁴R. Bender-Salazar, “Design Thinking as an Effective Method for Problem-Setting and Needfinding for Entrepreneurial Teams Addressing Wicked Problems,” *Journal of Innovation and Entrepreneurship* 12 (2023): 24, <https://doi.org/10.1186/s13731-023-00291-2>.

¹⁵Scharoun et al., “Understanding Design Culture from East to West: A Transdisciplinary Approach to Teaching.”

develop user-centred solutions in complex systems¹⁶, often incorporating expert insights and co-design with users¹⁷.

To foster culturally adaptable healthcare prototypes, the authors designed a design sprint integrating experiential and PBL approaches.

Case Study: Design For Change Study Tour

The authors facilitated a two-week learning experience for 108 design and health students from multiple international institutions. In June 2024 and 2025, participants travelled to Malaysia and Singapore to engage in a symposium and design sprint focused on healthcare sustainability. Students from diverse disciplines worked in multicultural teams. They examined healthcare systems through multidisciplinary perspectives to better understand end users and develop inclusive, actionable solutions. The program began with a symposium featuring global experts equipping students to address SDGs 3, 11, and 8. Experiential learning was further supported through cultural immersion activities and visits to healthcare facilities, exposing students to different practices, environments, and challenges. During a five-day design sprint, teams developed solutions informed by both multidisciplinary insights and cultural understanding, aiming to create tools that operate across cultural boundaries.

Results

The program provided students with experience in cross-disciplinary collaboration, a critical approach for addressing global challenges. It also fostered a sense of empowerment in navigating complex global issues. The project demonstrates how systems thinking, materials science, and design innovation can converge to support circular healthcare solutions.

To illustrate this, the design thinking process undertaken by student teams is outlined below.

Step 1: Problem Identification

After the symposium and site visits, teams identified key problems, such as sterile wrap waste, reframing it as an opportunity for circular innovation within a sector recognised as highly resource-intensive and emissions-heavy¹⁸, where plastic recycling rates remain low despite technical recyclability¹⁹, reflecting broader challenges in medical waste management systems²⁰, particularly in land-constrained contexts where waste disposal capacity is limited²¹.

¹⁶Anni Pakarinen et al., *Design Thinking in Healthcare: From Problem to Innovative Solution* (Springer Cham, 2023), <https://doi.org/10.1007/978-3-031-24510-7>.

¹⁷Jake Knapp et al., *Sprint: How to Solve Big Problems and Test New Ideas in Just Five Days* (Bantam Press, 2016).

¹⁸Matthew J. Eckelman and Jodi Sherman, "Environmental Impacts of the U.S. Health Care System and Effects on Public Health," *PLOS One* 11, no. 6 (2016): e0157014, <https://doi.org/10.1371/journal.pone.0157014>.

¹⁹United States Environmental Protection Agency, *Advancing Sustainable Materials Management: 2018 Fact Sheet* (EPA, 2020), https://www.epa.gov/sites/default/files/2020-11/documents/2018_ff_fact_sheet.pdf.

²⁰Elliott Steen Windfeld and Marianne Su-Ling Brooks, "Medical Waste Management – A Review," *Journal of Environmental Management* 163, November (2015): 98–108, <https://doi.org/10.1016/j.jenvman.2015.08.013>.

²¹National Environment Agency, *Semakau Landfill 20th Anniversary* (National Environment Agency, 2020), <https://www.nea.gov.sg/corporate-functions/resources/publications/books-journals-and-magazines/envision-lite/june-july-2020/semakau-landfill-20th-anniversary>.

Step 2: Stakeholder Analysis

Teams mapped system lifecycles and conducted stakeholder analysis, developing personas and journey maps to inform co-design processes.

Step 3: Prototype

Teams developed functional prototypes and presented them to industry panels, including concepts such as Enzima, which explores advanced recycling of sterile wrap waste²².

Step 4: Community Engagement

Student engagement was supported through visual communication strategies to promote awareness and adoption of sustainable practices.

Conclusion

Healthcare innovations with global relevance are developed by teams capable of navigating diverse cultures. Traditional education models often struggle to equip students with the interdisciplinary and systemic thinking needed to address complex challenges. The Design for Change initiative supports rapid innovation and cross-cultural understanding, which are essential for addressing healthcare sustainability.

Learning 1: Building Confidence and Cultural Awareness

Cultural intelligence is critical, and unfamiliar contexts challenge assumptions and foster innovation.

Learning 2: Transdisciplinary Approach to Innovation

Transdisciplinary approaches enhance problem-solving by integrating diverse perspectives across cultures.

Learning 3: Global Collaboration

Collaboration accelerates skill development and prepares students for global professional contexts.

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²²Prototype for Humanity, Enzima Project: Chemical Recycling of Sterile Wraps to Reduce Clinical Waste (Prototype for Humanity, 2024), <https://www.prototypesforhumanity.com/project/enzima/>.

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Part VII

Speculative

Chapter 50

GameShift Futures: Reimagining the University Through Speculative Play

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Abstract

On a bright July morning in 2025, a robot strolling down a Manhattan street greeted passersby—a scene that captures both the promise and the unease of our technological age. As Yogi Berra once said, “the future isn’t what it used to be”. The accelerating pace of change across technological, social, and institutional domains demands that higher education reimagine not only *what* it teaches, but *how* learning itself is structured. This chapter proposes game design and immersive media—what I term *expanded media*—as frameworks for rethinking pedagogy and institutional practice. Drawing on Anthony Dunne and Fiona Raby’s notion of design as speculation, I argue that expanded media serve as models for systems thinking, collaborative problem-solving, and iterative learning, offering higher education a methodology for cultivating adaptability and foresight in the face of uncertainty.

To test these ideas, I introduce *GameShift*, a prototype no-code, AI-assisted platform developed in collaboration with SeaMonster Studio (Cape Town) and gaming-impact expert Charles Gasper. *GameShift* enables faculty to design interactive experiences aligned with disciplinary content and learning objectives, translating principles of game design—choice, narrative, and interaction—into frameworks for classroom innovation. By reframing play as a mode of inquiry rather than distraction, the project explores how game-based methodologies can help universities prototype adaptive, student-centred learning environments. Ultimately, the chapter positions gaming and immersive media not as supplemental engagement tools, but as epistemic frameworks for an education system capable of navigating and co-creating futures that lie ahead.

Keywords: *Game-based Learning, Design Thinking, Expanded Media, Higher Education Innovation, Immersive Pedagogy, Speculative Design, Play as Methodology, AI-assisted Learning Design, Pedagogical Transformation*

Introduction

On a sunny July morning in 2025, a robot walked down the street in New York City, greeting curious onlookers with a warm hello, the kind of ‘futuristic’ scene we imagined decades ago. As Yogi Berra famously remarked, “the future isn’t what it used to be,” a paradox that captures the uncertainty shaping our present moment. Alongside a robot leisurely strolling through Manhattan, we contend with a fear of technology’s dominance over humanity, and the broader challenge of a literally unpredictable future, as conditions and visions change rapidly. While we can only make educated guesses about the future,

we certainly have the ability today to shape the future we want to see—and higher education, in its mission to prepare students, who have a vital role to play, both as future workers and as engaged citizens. The question is not just what skills, competencies, and professions universities should focus on, but also on how these are imparted. In other words, it is not just about what we teach, but how we teach it.

One vital framework for imagining the university of the future is gaming and immersive media, also known as expanded media. I take my cue from Anthony Dunne and Fiona Raby, who argue for design not as a process for making things, but as a means of speculating about how things could be¹. Focusing specifically on gaming and immersive media design, we can change not just what we teach, but how we teach it. Games do more than deliver content. They model systems and simulate possible futures, and, perhaps most important, they engage students in dynamic, participatory problem solving. Games bring interaction, the most salient feature of our digital age², fully into the university classroom.

As higher education faces escalating uncertainty, especially as universities weigh how to future-proof their students for a rapidly changing world, gaming and immersive media can provide critical tools for institutional transformation. Games can be used to prototype adaptive, student-centred, and technologically fluent learning environments, while challenging entrenched assumptions about curriculum, assessment, and structure. By cultivating agility, experiential engagement, and future-oriented thinking, expanded media equips students with tools suited to a world in which the future may be very different from what we imagine today.

The Challenges

Higher education stands at a critical juncture. As societies confront overlapping crises of information overload, institutional distrust, cognitive fragmentation, and economic inequity, the university must reimagine its role in preparing students not only for employment but for participation in an increasingly complex and unstable world. For that matter, the academy itself—with its entrenched rules and institutional procedures, operates on a temporal register that feels out of sync with the world beyond its walls—must also be reimaged to keep pace with this rapid pace of transformation. These challenges demand a recalibration of pedagogical priorities and institutional commitments to ensure that students graduate with core knowledge, as well as a flexible, adaptive toolkit for navigating and shaping the future of work, civic life, and global citizenship.

Recently, the nature of work—for which universities are meant to prepare many—has undergone a fundamental transformation, from shared physical space to distributed networks and asynchronous collaboration. Teams now operate across time zones, geographies, and cultural contexts. Preparing students for this new reality involves far more than teaching them to use Zoom or other remote communication tools. It requires fostering the interpersonal, strategic, and adaptive capacities needed to collaborate effectively in non-co-located environments. In this respect, game-based learning—

¹Anthony, Dunne and Fiona Raby, *Speculative Everything: Design, Fiction, and Social Dreaming* (Boston: MIT Press, 2013).

²Janet Murry, *Inventing the Medium: Principles of Interaction Design as Cultural Practice* (Boston: MIT Press, 2011).

especially in multiplayer or role-based formats—can serve as powerful rehearsals for the ambiguity, negotiation, and teamwork required in these emergent professional settings.

Universities must also focus on preparing students for civic life through the cultivation of critical literacy. As information is ever more ubiquitous, higher education's historical mission, to transmit knowledge, is less essential. Instead, the central pedagogical challenge becomes imparting an ability to evaluate the sources, contexts, and ideological underpinnings of what counts as knowledge, to combat the erosion of epistemic uncertainty. Students must be equipped to interrogate authority, assess credibility, and discern among competing narratives.

Compounding this challenge is a broader crisis of trust in public institutions, including those responsible for producing and disseminating knowledge, whether political, journalistic, scientific, or educational. As disinformation proliferates and institutional authority is repeatedly undermined or dismissed, the university's status as a trusted arbiter of knowledge has grown precarious. In response, higher education must not retreat into defensiveness or insularity. Instead, it must model transparency, deliberation, and intellectual accountability, all of which will offer students and society a renewed vision of public trust grounded in openness and rigor.

At the same time, our cognitive and affective landscapes are increasingly shaped by the relentless demands of digital life. Incessant notifications, multitasking pressures, and algorithmically engineered distractions have all fragmented our attention and reduced our capacity for sustained inquiry. One of the most urgent tasks for educators, therefore, is to design learning environments that retrain attention—with the conviction that focused attention is now as much an ethical stance as it is a cognitive skill. This requires pedagogical strategies that meet students where they are, including the integration of familiar tools like games, while also subverting their most addictive, dopamine-driven mechanics in favour of practices that promote deeper engagement and reflection.

All of this is unfolding within a broader socio-economic climate marked by increasing enclosure: the gating of information through media paywalls, algorithmic filters, and platform monopolies; the privatization of public discourse; and the rising costs of access to education itself. In this context, although knowledge may be seemingly available to all, the ability to critically assess and use that knowledge becomes increasingly inequitable. So, the university must make extra effort to resist further insulation and instead reassert its role as a public commons: a site for open inquiry, civic engagement, and the dismantling of intellectual and structural barriers.

Expanded Media: A Tool of Alignment

Games are often viewed as another form of entertainment media³, as is immersive media. Some advocates have excitedly promoted gamification—the application of game elements like points, levels, and rewards to non-game contexts—as a panacea for increasing engagement in education, business, and beyond⁴. However, both of these approaches miss their unique characteristics and potentials. I

³Colleen Macklin and John Sharp, *Games, Design and Play: A Detailed Approach to Iterative Game Design* (Boston: Addison-Wesley, 2016).

⁴Caponetto, I. et al., Gamification and education: A literature review. In *Proceedings of the 8th European Conference on Games-Based Learning*. Quoted in Dichev, C., & Dicheva, D, 2017, *Gamifying education: What*

propose game-based and immersive media not as merely supplemental tools, or as a lure for learning. Rather, I seek to draw on the underlying design principles and methodologies of games to build essential scaffolds and blueprints for contemporary education.

Gaming methodologies emphasise learning not as a linear transfer of knowledge, but as a dynamic, participatory process in which students navigate complexity, inhabit multiple perspectives, and rehearse decision-making. Take, for example, the practice of modding—altering or reconfiguring existing games to create new meanings, mechanics, or narratives. More than just a creative exercise, modding can be a powerful tool for exploration in higher education, as it invites students to critically engage with systems, rules, and structures, while encouraging them to intervene in and reshape inherited frameworks. When integrated into academic contexts, modding becomes a form of institutional play—a method through which students and faculty can reimagine disciplines, challenge dominant paradigms, and co-create more adaptive and inclusive educational ecosystems. In even more practical terms, modding can be an agile, low-cost strategy for prototyping curricular innovations, for instance, or fostering interdisciplinary collaboration and supporting learner-centred approaches to knowledge production.

This approach is, in many ways, curatorial, weaving together diverse approaches, texts, and contexts to create new meaning through juxtaposition and narrative structure. Educators adopting this methodology are engaged in assembling and staging heterogeneous practices into a coherent and intentional learning experience. Game-based learning and immersive media environments are not at odds with traditional lectures, challenge-based learning, and seminar discussions. Rather, all methods can be curated—sequenced, layered, and interwoven—in ways that heighten their respective strengths and compensate for their limitations. Through this lens, pedagogy becomes a form of intellectual and affective curation: creating a learning environment that is open-ended yet intentional, structured yet generative. It invites students not only to consume knowledge but to co-author it, thus facilitating an experiential and engaged form of learning.

Gameplay, in fact, is a great allegory for education. Games come with rules to define their parameters, but also suggest wonder, excitement, and discovery. The outcomes of a given game or lesson are not necessarily clear or defined but are shaped by the students. Play, Whitton points out, “offers a powerful counterpoint to performance-driven culture, inviting curiosity, freedom, and flow”⁵. Just as importantly, as a methodology it enables experimentation without the fear of failure.

If we adopt David Gauntlett’s position of games as ‘objects-to-think-with’, we begin to understand their value not merely as entertainment or EdTech tools, but as epistemic frameworks—means of modeling,

is known, what is believed, and what remains uncertain—A critical review. *International Journal of Educational Technology in Higher Education*, 14(9) <https://doi.org/10.1186/s41239-017-0042-5>; De Freitas, et al., 2010. Learning as immersive experiences: Using the four-dimensional framework for designing and evaluating immersive learning experiences in a virtual world.” *British Journal of Education Technology*, 41, no. 1 (2010), 69-85.; Gee, J. P., *What Video Games Have to Teach Us About Learning and Literacy* (New York: Palgrave Macmillan, 2003).

⁵Nicola Whitton, *Play and Learning in Adulthood: Reimagining Pedagogy and the Politics of Education* (Cham: Palgrave Macmillan, 2022).

testing, and iterating ideas in dynamic, interactive environments.⁶ In higher education, this positions game design principles as an effective means for critical inquiry and creative experimentation, allowing students to engage with complex systems, simulate alternative futures, and prototype responses to real-world challenges. Much like Gauntlett's use of physical media (such as LEGO blocks) to externalise and explore thought, game design as a methodology offers a procedural medium through which students can visualise abstract concepts, test relationships between variables, and reflect on the consequences of different choices across a variety of disciplines. This makes it particularly valuable for interdisciplinary learning, systems thinking, and the cultivation of flexible problem-solving skills—precisely the capacities needed to navigate an increasingly volatile world.

This is not about turning all matters of higher education into a game. Rather, it is an invitation for a paradigm shift, one that is premised on a bouquet of practices, with design thinking at its centrepiece. Games, in this context, become one among many tools. It is a shift that aligns with broader efforts in higher education to foster student agency and intrinsic experiential learning.

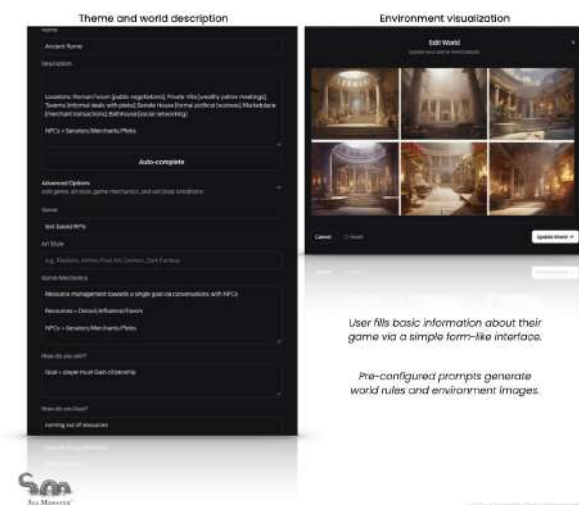
GameShift

To begin testing these ideas in practice, I am currently collaborating with gaming impact expert Charles Gasper and SeaMonster Studio in Cape Town to develop *GameShift*, a prototype platform that explores how game design methodologies might be mobilised within higher education. Conceived as a no-code, AI-assisted platform, *GameShift* is intended to allow instructors to design games aligned with curricular goals, in a way that requires no programming expertise. The prototype accommodates a range of formats, from role-playing simulations and branching narratives to board games and decision trees, thus enabling instructors to test how different ludic structures can translate into distinct modes of learning. Importantly, *GameShift*'s AI functions not as a producer of content in itself, but as a tool for scaffolding: it assists faculty in aligning scenarios, choices, and narrative arcs with disciplinary concepts and pedagogical objectives.

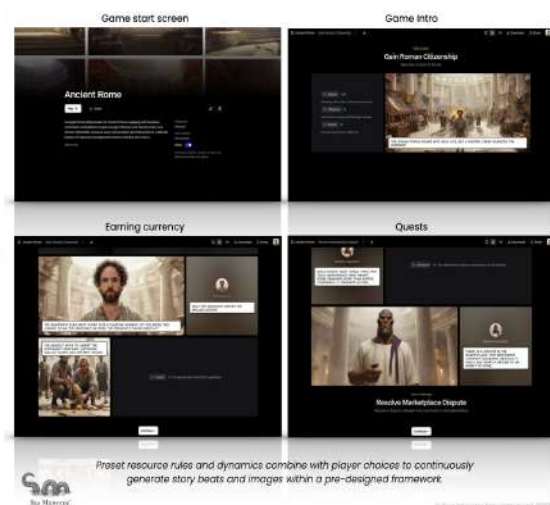
Early concept mockups

Early concept mockups

Game customization and setup



Storybook-based gameplay



⁶David Gauntlett, *Making is Connecting: The Social Meaning of Creativity, from DIY and Knitting to YouTube and Web 2.0.* (Cambridge, UK: Polity Press, 2011).

At this stage, *GameShift* should be understood less as a finished product than as a research environment for experimenting with the affordances of game logics—choice, contingency, narrative, and systemic interaction—in structuring educational experience. Its development highlights how games might be reframed not as supplementary ‘engagement tools’, but as epistemic frameworks through which knowledge is assessed, organised, tested, and transmitted. As such, the project does not resolve the questions posed in this essay but rather provides a site through which they may be advanced, debated, and refined.

Conclusion

In the decades ahead, the university must become a shared act of speculation—iterative, playful, and open-ended. Game design offers not a metaphor but a method: a way of staging uncertainty, distributing agency, and building worlds together. If higher education is to matter in 2050, it is because it has dared to redesign itself as a living, experimental commons, without always knowing or having a fixed outcome. It is about acquiring the skills of improvisation, critical foresight, and collaborative sense-making—the capacities to navigate complexity, anticipate and nimbly address emergent challenges, and co-create meaningful possibilities in a world that will continue to be defined by constant flux.

Acknowledgements

The research for this presentation was significantly supported by my Higher Education Academic Leadership Fellowship at Montclair State University and my time as a Visiting Scholar at the NYU Game Center in 2024–25. I am especially grateful to Junius Gonzales, Kenneth Sumner, and Emily Isaacs at Montclair State for their support of my work, and to Naomi Clark and Eric Zimmerman, who warmly welcomed me into the gaming community at NYU and inspired much of my thinking on the subject.

Declaration

The authors declare that artificial intelligence tools were used in the preparation of this manuscript. The use of these tools was limited to assisting with grammar and language, and all outputs were carefully reviewed, verified, and edited by the authors to ensure accuracy, originality, and alignment with academic standards. The authors take full responsibility for the content of this manuscript, including any sections that were supported by AI tools. No AI system was used to generate original research findings, interpret results independently, or draw conclusions without human intervention.

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Chapter 51

Prototypes of Personalisation and Customisation for Next-generation Medicines

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Abstract

The growing demand for personalised medicine has highlighted the limitations of conventional drug delivery systems, which often fail to address individual variability in genetics, lifestyle, and therapeutic responses. Advances in personalised therapy have necessitated flexible manufacturing platforms capable of producing patient-specific dosage forms. Pharmaceutical additive manufacturing (PAM), particularly 3D/4D printing technologies, has emerged as a disruptive tool that enables the on-demand fabrication of individualised drug delivery systems. Techniques such as fused deposition modelling (FDM), stereolithography (SLA), selective laser sintering (SLS), semi-solid extrusion (SSE), and direct powder extrusion (DPE) facilitate customisable geometry, dosage, drug release kinetics, multidrug layering, and stimuli-responsive behaviour. This chapter discusses the recent progress in PAM for personalised medicine, outlining its potential to revolutionise therapeutic precision and patient adherence through digitally controlled pharmaceutical fabrication.

Keywords: *Pharmaceutical additive manufacturing, 3D/4D printing, Personalised medicine, Drug delivery systems, Patient-specific dosage forms*

Introduction

Conventional drug development has successfully investigated specific pharmacological agents for the development of high-quality medications. However, targeting several mechanisms simultaneously may be more effective than single-drug regimens. Different transmission routes can be modulated in a synergistic or additive manner using a combination of drug treatments¹. The landscape of modern healthcare is undergoing profound transformation with the advent of personalised medicine, a therapeutic approach that seeks to tailor medical treatment to the unique genetic, physiological, and lifestyle characteristics of each individual. Pharmaceutical additive manufacturing (PAM) and rapid prototyping have advanced significantly in the pharmaceutical sector because of the demand for versatile, individualised, and customisable products. Pharmaceutical products with intricate geometries and structures, which are challenging to fabricate using traditional production techniques, can be developed using 3D printing. 3D printing is an AM technique that uses computer-aided design (CAD)

¹Serena Boccella et al., "Combination Drug Therapy for the Management of Chronic Neuropathic Pain", *Biomolecules*, 13, no. 12: 1802 (2023).

to fabricate customised objects layer by layer. 3D printing enables the production of personalised medications in small quantities with tailored dosages, release profiles, and multi-drug combinations, addressing individual variations in physiology, genetics, lifestyle, and the needs of vulnerable populations such as paediatric, geriatric, and chronically ill patients². Recently, there has been an increase in the number of scientific publications and patents detailing the pharmaceutical uses of 3D printing, which indicates the growing interest in this method within the pharmaceutical sector owing to its benefits. The FDA authorised the first 3D-printed drug product in August 2015, which benefited 3D printing as a method of pharmaceutical manufacturing³.

As the pharmaceutical industry moves towards digitally enabled patient-centric care, PAM technologies present an unprecedented opportunity to bridge the gap between standard production and personalised therapy. This chapter discusses the importance of personalised drug delivery, the core technological advancements supporting it, and the potential impact of pharmaceutical 3D/4D printing on revolutionising healthcare.

Lab of Additive Manufacturing in Pharmaceuticals (LAMP)

The Lab of Additive Manufacturing in Pharmaceuticals (LAMP) is a specialised research facility focused on the design, development, and advancement of pharmaceutical 3D and 4D printing technologies. The primary objective of our LAMP is to develop personalised and customised medicines using cutting-edge additive manufacturing tools such as fused deposition modelling (FDM), stereolithography (SLA), semi-solid extrusion/direct powder extrusion (SSE/DPE), and selective laser sintering (SLS).

Our lab pioneers the fabrication of next-generation medicines, including nano-filled capsules, sintered printlets, microneedles, patches, bilayered pills, QR-coded films, ghost tablets, sorbents, and responsive 4D constructs. These innovations aim to meet the growing demand for precision drug delivery, especially in areas such as chronic diseases, paediatric care, and implantable systems. By merging pharmaceutical science, materials engineering, and additive manufacturing, LAMP is positioned at the forefront of transformative healthcare technologies—enabling a shift from conventional mass production to highly individualised therapy.

3D Printing Techniques

The tremendous versatility of 3D printing technology makes it an excellent choice for creating drug delivery systems (DDSs) with dimensions and designs that are difficult to achieve using traditional techniques. Our research exclusively focuses on various platform technologies for the development of personalised DDSs.

Key technologies in PAM include:

²Subham Banerjee, ed., *Additive Manufacturing in Pharmaceuticals*, (Springer, 2023).

³Jiaxiang Zhang et al., "Pharmaceutical Additive Manufacturing: A Novel Tool for Complex and Personalized Drug Delivery Systems," *AAPS PharmSciTech*, 19, no. 8 (2018): 3388-3402.

- **Fused deposition modelling (FDM)** drugs and polymers are first extruded using a hot-melt extruder (HME) to prepare filaments, which are then coiled on a spool to prepare them for printing. The printer deposits the developed 3D object onto the printing platform by pulling the filament from the spool and allowing it to extrude through the pre-heated nozzle. It utilises thermoplastic polymers to fabricate oral dosage forms with precise control over geometry and internal structure.
- **Stereolithography (SLA)** when exposed to UV or visible light, the photoreactive liquid resin initiates a photopolymerisation reaction. This process is initiated by the production of free radicals in the photoinitiator and the formation of a covalently crosslinked network. SLA offers high precision and resolution, making it suitable for use in intricate dosage forms and implantable devices.
- **Selective Laser Sintering (SLS)** works primarily by projecting a laser beam onto the surface of a powder bed containing the polymer and drug. This caused the powder to instantly sinter by increasing the temperature of the powder bed. New layers of powder are repeatedly spread over the sintered ones using a roller until the 3D object is fully formed. This allows the creation of porous solid dosage forms, ideal for controlled and sustained drug release.
- **Semi-solid Extrusion (SSE) and Direct Powder Extrusion (DPE)** involve the extrusion of pastes or gels under pressure, which is ideal for incorporating heat-sensitive drugs. DPE facilitates direct extrusion of powder blends without prior filament formation. Proper ink characteristics and appropriate printing parameters, such as pressure, speed, and nozzle size, are necessary for effective printing as they enable accurate dosing and layering of numerous medications. This method reduces the number of processing steps and is suitable for high drug load formulations (Figure 1).

3D Printed Dosage Forms

The literature provides a number of demonstrations of 3D printed dosage forms that were developed in our lab, and use of various polymers and processes. Examples of 3D printed formulations are covered in this section.

Tablets

Using 3D printing to manufacture tablets allows the development of tablets with various geometric and medication release patterns. In our study, tablets were printed using a SmartEx QD 100 polymer with isoniazid through an SLS 3D printer, which showed immediate gastric release within 15 minutes⁴.

⁴Tukaram Karanwad et al., "Additive manufacturing of SmartEx QD 100 designed oral three-dimensional printlets containing isoniazid for immediate gastric release by selective laser sintering", *Molecular Pharmaceutics*, 21, no.10 (2024): 5272-5284.



Figure 1: Thrust research areas of LAMP.

Implants

Drugs can be successfully delivered to the site of action for a prolonged period via implants. In our lab, prolonged delivery of tenofovir was achieved using a subcutaneous hydrogel-based porous implant. The implant was fabricated using an SSE 3D printer with a methyl cellulose-reinforced BSA hydrogel. The hydrogel exhibited shear thinning and self-healing behaviours, and the implant showed thermal stability, cytocompatibility, and sustained release behavior over 28 days⁵.

⁵Marepally Karthik Venkat Sai Sharan et al., "3D printed subcutaneous implant for prolonged delivery of tenofovir with desired release capability, biocompatibility, and viability," *Journal of Molecular Structure*, 1319 (2025): 139559.

Microneedles

Microneedles can puncture the skin and deliver drugs directly into the dermis, making them highly effective for transdermal drug delivery. In our study, the transdermal delivery of ceftriaxone was achieved using hollow microneedles. Bio-inspired labrum tip microneedles were fabricated using an SLA 3D printer with biomed amber resin. The microneedles exhibited efficient penetrability through porcine skin within 18 hr and excellent bioavailability.⁶

Capsules

In our lab, sustained release of levofloxacin was achieved using a gastro-retentive floating-hollow capsular device. The capsule was developed using a SLS 3D printer employing Kolliphor P188 and Kollidon SR. The capsular device exhibited prolonged delivery to the gastric region⁷.

Films and hydrogels

Our lab fabricated dental 3D-printed oral films using CompactCel® polymers loaded with diclofenac sodium via SSE 3D printing for toothache management. The films demonstrated an initial burst release followed by sustained drug release over 150 min⁸. Similarly, Aspirin-loaded, QR-encoded enteric films were fabricated using Kollicoat® MAE 100P and PLA via FFF 3D printing for targeted intestinal delivery. The films showed enhanced release at alkaline pH, suitable for enteric delivery, while the QR code enabled patient access to detailed drug information⁹. Similarly, oral films were prepared using a self-healing mineralised hydrogel with diclofenac sodium using an SSE bioprinter. The films showed an increased pore size, faster release, and considerable bioavailability to the targeted area¹⁰.

Conclusion and Future Perspectives

3D and 4D printing are transforming pharmaceutical science by enabling patient-specific drug fabrication with precise dosing, shape, and release profiles, thereby enhancing treatment efficacy and safety. Advancements in 4D printing are driving the development of smart medicines that respond dynamically to physiological conditions, offering significant potential for personalised, paediatric, and geriatric care, as well as targeted and controlled drug delivery. 3D printing has introduced new

⁶Shubham Kawre et al., "Bioinspired labrum-shaped stereolithography (SLA) assisted 3D printed hollow microneedles (HMNs) for effectual delivery of ceftriaxone sodium," *European Polymer Journal*, 204 (2024): 112702.

⁷Ganesh Pandav et al., "3D printed gastroretentive floating-hollow capsular device (GRF-HCD) for levofloxacin oral delivery using selective laser sintering (SLS) platform technology," *Journal of Biomaterials Science, Polymer Edition* (2025): 1-18.

⁸Rohit Bhawale et al., "Three-dimensional (3D) printing of oral dental films (ODFs) using blended Compactcel® polymers through semi-solid extrusion (SSE) bioprinter", *Bioprinting*, 33 (2023): e00287.

⁹Thotapalli Lahari et al., "Quick response-encoded chip engraved onto multifunctional aspirin loaded enteric films by fused filament fabrication-3D printing," *Journal of Applied Polymer Science*, 141, no. 8 (2024): e55048.

¹⁰Nachiketa Palit et al., "3D Printable Self-Healing Mineralized Hydrogels Loaded With Diclofenac Sodium: In Vitro and In Vivo Assessment," *Biotechnology and Bioengineering*, 122, no. 6 (2025): 1530-1540.

manufacturing paradigms, enabling local and decentralised production. Future advancement requires strong regulatory frameworks and close collaboration among researchers, healthcare professionals, and regulatory bodies to fully harness its potential.

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Zhang, Jiaxiang, Anh Q Vo, Xin Feng, Suresh Bandari, and Michael A Repka. November 2018. "Pharmaceutical additive manufacturing: A novel tool for complex and personalized drug delivery systems." *AAPS PharmSciTech* 19 (8): 3388–402. doi:10.1208/s12249-018-1097-x.

Chapter 52

The Role of Design in Challenging Exclusionary Urban Spaces

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Abstract

Too often, the design of public space goes unquestioned. Its materials, forms, and functions are accepted as neutral, yet everyday objects quietly shape who feels welcome and who is excluded. This paper examines how design makes visible the unnoticed forms of exclusion embedded in urban environments. It focuses on hostile architecture in London and interventions that restrict the use of public space by people experiencing homelessness. The research adopts interrogative and socially engaged, practice-led methods to explore how spatial decisions reinforce inequality.

A central case study used digital fabrication to reproduce examples of hostile design. These 3D printed artefacts were used in a pedagogical setting with design students as tools for critical enquiry. Handling and analysing objects encouraged students to consider how design influences behaviour, reinforces boundaries, and shapes the daily lives of marginalised groups. The artefacts are positioned as transferable tools for engagement with public, professional, and policy audiences.

The chapter draws on Gibson's theory of affordances to examine how public spaces communicate what is permitted or denied and engages with Petty's critique of exclusionary design as a material expression of social control. This approach demonstrates how small-scale interventions can generate wider conversations on inclusion, empathy, and responsibility in public spaces.

Keywords: *Hostile Architecture, Public Space, Spatial Justice, Affordances, Social Exclusion*

Introduction

Urban design is a site of political contestation. Decisions about the shape of a bench, the placement of a barrier, or the use of spikes on surfaces may appear technical but carry significant consequences for who is permitted to occupy space. This chapter investigates the role of design in the production and maintenance of exclusionary public spaces, with a particular focus on the material strategies of hostile architecture. In recent years, debates around hostile architecture have drawn attention to how design is employed to regulate behaviour and, in many cases, to exclude those whose presence is considered undesirable. Spikes on pavements, benches segmented to prevent lying down, and barriers designed to deter loitering are among the most visible examples. These interventions are often justified as measures to ensure safety or order, but they are better understood as material manifestations of social control¹.

¹James Petty, 'The London Spikes Controversy: Homelessness, Urban Securitisation and the Question of 'Hostile Architecture'', *International Journal for Crime, Justice and Social Democracy* 5, no. 1 (2016): 67–81. Accessed July 21, 2025 <https://doi.org/10.5204/ijcjsd.v5i1.286>.

This chapter examines hostile architecture through a London case study that reproduces exclusionary design objects using 3D printing. These artefacts were introduced into a pedagogical context, yet their significance extends beyond the studio. The central argument advanced here is that reproducing hostile design through digital fabrication can serve as a critical method for engaging diverse audiences in debates on spatial justice. The artefacts operate as methodological tools that render exclusion visible and tangible. By materialising hostile design in forms that can be handled and re-contextualised, the project shows how practice-led research can highlight complex social issues in ways that resonate across academic, professional, public, and policy contexts.

Hostile Design and Affordances

Urban space communicates expectations about use and behaviour through what Gibson has described as ‘affordances’; the perceived possibilities for action offered by a given environment². When a bench affords sitting but not lying down (Figure 1), or when spikes afford deterrence rather than comfort, the built environment actively shapes who belongs and who does not. The concept of affordances is therefore central to understanding hostile design. While Gibson developed the term in relation to perception and action, subsequent scholarship has shown how affordances emerge within the interpretive and regulatory environments in which they operate³.



Figure 1: The Camden bench in London, designed to restrict certain uses of public space (Image: A. Bennie, 2021).

²James J. Gibson, *The Ecological Approach to Visual Perception: Classic Edition* (Oxford: Taylor & Francis Group, 2014), Accessed December 2024, ProQuest Ebook Central.

³Donald A. Norman, *The Design of Everyday Things* (New York: Basic Books, 2013).

Hostile architecture exploits affordances to restrict or deny certain behaviours, often targeting vulnerable populations such as people experiencing homelessness. What appears to be a practical design choice is in fact a political gesture. Petty situates hostile architecture as a material expression of urban policy, enforcing social control through physical means⁴. Rather than addressing the structural conditions of homelessness, these design interventions remove its visibility from urban space. Hostile design embodies broader dynamics of exclusion, such as the displacement of those whose needs do not align with dominant expectations of order or safety.

It is also useful to contrast hostile architecture with crime prevention through environmental design (CPTED). Cozens and Love observe that CPTED seeks to prevent crime by enhancing surveillance, improving lighting, and nurturing social cohesion, but it does not necessarily target specific populations for exclusion⁵. Hostile design, in contrast, operates more directly to regulate who is present in public spaces, often without accountability. This comparison emphasises how urban policies may appear ordinary while concealing the social control mechanisms embedded in everyday materials.

Historically, street furniture and spatial configurations have regulated behaviour, from anti-skateboarding studs to gated squares⁶. Contemporary hostile design is distinguished by its quiet integration into the urban landscape. The hostility is often obscured through the language of safety or maintenance, yet it functions to remind certain bodies that they are out of place. Understanding hostile design through affordances reveals both the material strategies at work and their embodied consequences.



Figure 2: Public bench in Central London illustrating subtle strategies of exclusion (Image: A. Bennie, 2020).

⁴James Petty, 'The London Spikes Controversy: Homelessness, Urban Securitisation and the Question of 'Hostile Architecture'', 72–73.

⁵Paul Cozens and Terence Love, "A Review and Current Status of Crime Prevention through Environmental Design (CPTED)," *Journal of Planning Literature* 30, no. 4 (2015): 393–412 <https://prohic.nl/wp-content/uploads/2021/02/166-15feb2021-CPTEDReview.pdf>.

⁶Steven Flusty, *Building Paranoia: The Proliferation of Interdictory Space and the Erosion of Spatial Justice* (Los Angeles: Los Angeles Forum for Architecture and Urban Design, 1994).

Affordances emerge through embodied experiences in space. Hostile architecture makes this experience tangible and shapes behaviour and feelings of welcome or exclusion. By reproducing these designs as 3D-printed artefacts, the project makes the politics of exclusion material perceptible and provides a platform for critical enquiry.

Case Study and Methods

The case study examined hostile design interventions in central London. Examples included segmented benches designed to prevent lying down, curved seating that limits rest, and pavement spikes that deter loitering. These interventions were chosen for their recognisability and the clarity with which they express exclusionary intent. Each was photographed, measured, and modelled digitally before being reproduced through 3D printing at a reduced scale.

3D printing served two purposes. First, it enabled accurate replication of exclusionary design forms while keeping them portable. Second, it positioned the project within a practice-led research methodology. By reproducing hostile design objects, the project translated acts of exclusion into tangible artefacts that invited closer critical engagement. These artefacts became tools for reflection rather than instruments of exclusion.



Figure 3: 3D printed artefacts of hostile design (Image: A. Bennie, 2023).

The artefacts were introduced in pedagogical workshops with product and furniture design students, who engaged with them through touch, observation, and discussion. This hands-on encounter allowed participants to recognise the embodied impact of hostile design beyond abstract description.

The project also shows that these artefacts function as transferable methodological tools suitable for community settings, professional contexts, and policy forums. Their tactility supports participants engagement with material politics of exclusion in ways that textual or visual media cannot. The workshop structure offers clear means of examining how design shapes public space and prompts critical dialogue across diverse audiences.

This approach aligns with Dewey's conception of art and design as forms of public enquiry which render shared problems perceptible and debatable⁷. The artefacts operate as probes that draw attention to the politics of urban space, enabling audiences to encounter exclusion viscerally rather than abstractly.

⁷John Dewey, *Art as Experience* (New York: Putnam, 1934).

Similarly, Binder et al. describe design experiments as ‘things to think with’ that facilitate reflection and dialogue⁸. In this project, the artefacts functioned in this way as critical tools that provoke discussion and ethical reflection rather than as solutions.



Figure 4: Demonstrating artefacts in the workshop with students (Image: A. Bennie, 2023).

Discussion

The workshops demonstrated that materialising hostile design through 3D printing can open new ways of understanding. Students reported that handling the artefacts heightened their awareness of how design communicates inclusion or exclusion. One participant noted that ‘handling the artefacts made it impossible not to see these features in the city anymore and how such designed objects organise behaviour’. Another student described a sketch of an alternative bench configuration that adapted the central divider into a shared backrest, reframing the object’s affordance towards comfort and inclusion. These responses indicate how direct engagement with the artefacts prompted students to consider the ethical implications of urban design and how small adjustments might support more inclusive spatial encounters. Compressed into portable, scaled-down objects, these forms foreground the embodied consequences of spatial decisions that might otherwise go unnoticed.

The approach extends beyond teaching. In community contexts, the artefacts could enable public audiences to articulate experiences of exclusionary design. They provide accessible points of entry for

⁸Thomas Binder, et al., *Design Things*, illustrated edition (Cambridge, MA: MIT Press, 2011).

discussion, allowing communities to engage with material examples rather than abstract concepts. In this way, the workshops operate as platforms for collective reflection on the design of public space.



Figure 5: Participants handling 3D printed hostile design artefacts (Image: A. Bennie, 2023).

For professionals, the artefacts could support critical reflection on ethical responsibilities. Designers and urban planners work under competing pressures, from client demands to policy constraints. Introducing hostile design artefacts into professional discussion makes visible the trade-offs implicit in such decisions and encourages consideration of more inclusive alternatives.

While this paper positions 3D printed artefacts as transferable tools for engagement with professional, public, and policy audiences, empirical evidence of such external application is not yet available. Acknowledging this limitation points to an important direction for future research. Subsequent research will examine how these artefacts can support engagement, reflection, and advocacy beyond the studio, offering insight into their broader implications on spatial justice.

Policy engagement represents a particularly significant extension. Hostile design is often implemented without public consultation or oversight. The artefacts offer policymakers tangible evidence of exclusion embedded in the built environment. By materialising exclusion, they make visible consequences that data or reports alone may fail to convey. Ahmed emphasises how institutions often present themselves as neutral while reproducing inequity⁹. Similarly, hostile design presents as functional or aesthetic but embeds exclusionary tactics. These artefacts can help policymakers and civic organisations confront such dynamics directly.

The project demonstrates how practice-led research can bridge academic, public, and policy contexts. Reproducing hostile design as tangible artefacts turns subtle spatial interventions into subjects of debate, opening new ways to critique and challenge spatial norms.

⁹Sara Ahmed, *On Being Included: Racism and Diversity in Institutional Life* (Durham, NC: Duke University Press, 2012), accessed September 1, 2025, ProQuest Ebook Central <https://www.cmc.edu/sites/default/files/2022-03/Sara%20Ahmed%20On%20Being%20Included.pdf>.



Figure 6: Conceptual diagram for future engagement (Image: A. Bennie, 2024).

This discussion also points to the pedagogical and social potential of the artefacts, which act as catalysts for dialogue across audiences, from students to policymakers, amplifying the visibility of exclusion and inviting contestation.

Conclusion

Hostile architecture operates as a subtle yet pervasive form of social control that shapes who is welcome in urban space. By reproducing these interventions through 3D printing, this project exposes the politics embedded in everyday objects and reframes them as critical artefacts. These artefacts function as methodological tools that extend beyond the studio and support engagement across academic, community, professional, and policy contexts.

The project contributes to debates on spatial justice by showing how practice-led methods can make exclusion tangible and perceptible to diverse audiences. Small-scale design interventions can provoke wider conversations about inclusion, empathy, and responsibility in public space. The research highlights that design shapes not only what the environment affords but also who is excluded.

Through reproduction and recontextualisation, the project affirms the capacity of practice-led research to intervene in complex social issues. The artefacts act as prompts for reflection and critique and invite reconsideration of what public space affords and to whom.

If design can reproduce exclusion with subtlety, it must also be capable of supporting more inclusive futures. The task is not merely to expose exclusion but to insist that design remains accountable to justice and dignity in shaping urban life.

Declaration

The authors declare that artificial intelligence tools were used in the preparation of this manuscript. The use of these tools was limited to assisting with grammar and language, and all outputs were carefully reviewed, verified, and edited by the authors to ensure accuracy, originality, and alignment with academic standards. The authors take full responsibility for the content of this manuscript, including any sections that were supported by AI tools. No AI system was used to generate original research findings, interpret results independently, or draw conclusions without human intervention.

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Chapter 53

Gastroludology: Gastronomy Meets Ludology

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Abstract

Food and drink invite play. Play with flavours, textures, and appearance, play as part of the preparation, delivery, and presentation, and play as part of the act of eating and drinking. As such, food provides nourishment for the soul as well as the body. Conversely, the consumption of food and drink is bound and regulated by social and cultural norms which at times conflict with the notions of play, for example the old exhortation to children not to play with their food so as not to waste precious food or time. Furthermore, while the appearance and sound of food and eating are easy to capture and mediate as exemplified by countless media examples, the gustatory (taste) and olfactory (smell) elements of food are incredibly difficult to define and convey. In our work, we aim to break new ground by exploring the challenges and potentials of human food interaction.

Keywords: *Food, Play, Experience, Interaction, Gastronomy, Communication*

Introduction

Food and drink invite play. Play with flavours, textures, and appearance, play as part of the preparation, delivery, and presentation, and play as part of the act of eating and drinking. As such, food provides nourishment for the soul as well as the body.

Conversely, the consumption of food and drink is bound and regulated by social and cultural norms¹ which are at times in conflict with the notions of play², for example the old exhortation to children not to play with their food³ so as not to waste precious food or time. Thus, outside of the playful flair exhibited by cooks, hosts, and waiters or where it has become part of tradition (e.g. hiding the Afikoman during a Passover dinner⁴), playing with food has been constrained to the hidden margins where boundaries are broken, such as the feeding of small children⁵ (e.g. “here comes the aeroplane”), wild parties, and romantic interludes⁶.

¹Visser, Margaret, *The Rituals of Dinner*. (Pennsylvania State University, 1991).

²Caillois, Roger, *Man, play, and games*. (University of Illinois Press, 2001).

³Mechling, Jay, Don't Play with Your Food. *Children's Folklore Review*, *American Folklore Society* 23 no. 1 (2000): 7-24.

⁴Sherman, Sharon. R, *The Passover Seder: Ritual Dynamics, Foodways, and Family Folklore*. In Counihan, Carole (Ed). *Food in the USA* (Taylor and Francis, 1988).

⁵Orrell-Valente, Joan K., et al., “Just Three More Bites”: An Observational Analysis of Parents' Socialization of Children's Eating at Mealtime, *Appetite*, 48 no. 1 (2007): 37-45.

⁶Cole Ellen, et al., *Women's Conflicts About Eating and Sexuality: The Relationship Between Food and sexuality*. (Haworth Press, 1992) <https://doi.org/10.4324/9781315820651>.

As a result, although food and drink have featured prominently as a motif in art⁷ and form an integral part of religious and cultural practices from the ancient practice of sharing bread to the modern practice of sharing food photos, the notion of literally playing with food, that is utilising food as an element of play either on its own or as part of a game as opposed to playing with its flavours, textures, and appearance as part of its preparation or presentation has only recently begun to be explored.

In addition, our experience of food is highly visceral and thus while the appearance and sound of food and eating are easy to capture and mediate as exemplified by countless media examples, the gustatory (taste) and olfactory (smell) elements of food are incredibly difficult to define and convey. In our work, we aim to break new ground by exploring the ways in which we can harness the opportunities and traverse the challenges associated with our interactions with and through food.

The Physical Affordances of Food

As noted above in recent years there have been some novel explorations of food and digital technology. However, despite the great diversity and innovation exhibited in these various approaches and applications, the majority do not utilise food as an element of play, and those that do, do so in the established paths of the culinary arts and game design in which the cook continues to play with the flavour, texture, and presentation of the food albeit with the addition of digital technology and the game designer starts using real apples⁸, straws, and chocolates but continues to relate to them as symbolic tokens instead of making use of their inherent potential for play.

But why should we restrict ourselves in such a way? The physical properties of food and the rituals of eating hold within them an inherent potential for play such as (1) the opportunities for creative deconstruction and manipulation offered naturally by foods such as oranges with their peels and segments, and cobs of corn with their rows of kernels, or by design, by biscuits with serrated edges or by cookies with their layers of cream and pastry; (2) the element of chance offered by the spiciness of chili peppers; (3) the timing mechanisms that follow from the ripening of a banana or the temperature of an ice cream; (4) the magic circle⁹ that is formed as one fills a plate at a buffet table, bites into a pita bread, or reaches across a table for a shared dish; (5) the delicate balance between physical action, taste, and texture encapsulated in the act of dipping a churro in hot chocolate or a piece of sushi in soy sauce; (6) the rhymes and rhythms involved in the use of forks, knives, spoons, and chopsticks; the acts of licking, biting, and chewing; and the challenges presented by dishes like spaghetti or xiaolongbao; and (7) “the music of mastication”¹⁰ and other sounds associated with the act of eating or the process of digestion.

To date these properties of food and aspects of eating have only just begun to be explored, and as such these explorations have primarily focused on issues of perception and/or specific applications of

⁷Ferry, Jane F, *Food in Film: A Culinary Performance of Communication* (Routledge, 2003).

⁸Arnold, Peter, et al., “You Better Eat to Survive”: Exploring Cooperative Eating in Virtual Reality Games, TEI '18, ACM (2018).

⁹Huizinga, Johan, *Homo Ludens: A Study of the Play Element in Culture* (Beacon, 1955).

¹⁰Rossen, Jake, *The Science Behind Why We Crave Loud and Crunchy Foods* (Mental Floss, 2018).

technology¹¹. We propose the need to uncover, analyse, and categorise the various properties, affordances, mechanics, and procedural rhetorics¹² of food and eating and map them to the mechanics, dynamics, and aesthetics of play and games both as a means of enriching our mechanics vocabulary and as a means of better understanding the set of mechanics regardless of how we choose to define them.

Eating like the practise of sports has a physiological effect on the body and thus play with food like any sport or physical challenge will need to be carefully balanced. In addition, food also presents unique challenges which are not normally part and parcel of game design, namely palatability and wholeness. In traditional games, be they physical or digital, the players are not concerned with the palatability of the game tokens or the hygiene of the playing surface as they are neither going to eat the tokens nor use the play surface for eating. Yet, if eating is an integral part of the game this becomes a matter of prime concern both from a food safety¹³ perspective and from individual notions of hygiene and palatability. Furthermore, in traditional games all the elements of the game are considered to be complete, i.e. all the pieces on a chess board are assumed to be whole and not broken, etc. However, in a game in which eating is part of the narrative of play this cannot be assumed as a given, as any element may be eaten in whole or in part during the course of the game. This brings a whole new set of challenges and potentials to the game; how would we play a game of chess in which we have half a king and a quartered queen? How far can we push this physical form of pixelisation?

Overcoming Physical Constraints Through Digital Technology

Beyond the challenges and opportunities offered by the physical properties of food and the acts of eating and drinking lie a whole host of associated challenges which we have begun to explore by weaving together strands of the physical and the digital. Among them are:

- Exploring the use of animation and gamification to engage children with eating vegetables.¹⁴
- Exploring how to effectively communicate the spiciness of food through virtual taste sensations.¹⁵
- Exploring the use of haptics in the communication of texture in botanic and gastronomic inquiries.¹⁶
- Exploring sonic interactions for augmenting and/or regulating the experience of eating.¹⁷

¹¹Spence, Charles and Carlos Velasco, *Digital Dining: New Innovations in Food and Technology* (Springer, 2025).

¹²Bogost, Ian, *Persuasive Games: The Expressive Power of Videogames* (MIT Press, 2007).

¹³Motarjemi, Yasmine, (Ed.), *Encyclopaedia of Food Safety* (Academic Press, 2013).

¹⁴Wissigkeit, Tobias, *Motivating children to eat vegetables by enhancing meals with digital media*, Unpublished Thesis, (HSRW, 2019).

¹⁵Ladani, Siddhi, *An exploratory study of how to effectively communicate the level of hotness/spiciness of food items*. Unpublished Thesis, (HSRW, 2022).

¹⁶Pinson, Annie, *Exploring a Haptic Herbarium: Investigating Engagement with Digitised Plant Specimens through Haptic and Pseudo-Haptic Interaction*, Unpublished Thesis, Goldsmiths, the University of London (2025).

¹⁷Ge, Ruixan, *Sonic Interaction in Eating: Exploring Chewing Rhythm and Sound Feedback*, Unpublished Thesis, Goldsmiths, the University of London (2025).

- Exploring the limits and possibilities of asynchronous social interaction with and through food.¹⁸

We are also beginning to explore more conceptual challenges such as how to imbue purely digital objects such as emojis with taste and smell as for some there is a direct mapping, like a rose or a pineapple, and thus the challenge is in representing the smell but for others, such as a smiley, there is no direct mapping and thus the challenge is discovering how they are perceived, whether they are universal or culturally dependent and how they can be effectively conveyed across media, language, and culture.

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¹⁸Hwang, Saenarae, 2025, *Asynchronous social eating: Reimagining the Limits and Possibilities of Asynchronous Interaction*, Unpublished Thesis, Goldsmiths, the University of London.

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Chapter 54

From Walls to Worlds: Co-creating Heritage Narratives with AR Murals

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Abstract

Exploring the definition of heritage as a set of relationships with the past, this research looks at obstructions in equitable access to heritage. Recent decades saw heightened interest in intangible heritage, driven by digital media's use for transmitting heritage. Immersive technologies enrich on-site experiences and virtual tours, challenging narratives, power dynamics, and access to heritage sites.

In places like Egypt, local inhabitants are often excluded from economic gains from tourism and denied agency over heritage narratives, resulting in a loss of ownership.^{ss} This research investigates how augmented reality (AR) murals can facilitate equitable heritage management through education, participation, and diverse discourse, while also evaluating the inherent technological risks. Methodologically, it defines tangible and intangible heritage notions for **marginalised communities** and frames IT's role through heritage theory and prototypes. A comparative analysis of AR projects in Cairo, India, China, and Europe informs solutions for participatory design.

Keywords: *Augmented Reality (AR) Murals, Cultural Heritage Preservation, Intangible Heritage, Participatory Design, Digital Restoration*

Introduction

Augmented reality (AR) murals stand at the intersection of street art, digital media, and heritage^{1,2} preservation, transforming static walls into interactive experiences through overlaid animations, sound, or narrative³. Heritage is more than monuments; it is a living relationship between people and the past, frequently reflecting unequal power dynamics⁴. In many developing nations reliant on tourism, communities are excluded from heritage narratives and economic benefits. Digital tools such as AR offer ways to document, share, and interpret heritage, but they also raise questions about representation, authenticity, and access. This article assesses how AR murals can serve as catalysts for inclusive heritage

¹Gregory Ashcroft defines heritage as the use of the past for contemporary purposes, including political and social ones (Ashworth, 2008).

²Al-Ibrashy, May, 'Heritage in the Street: Megawra | BEC's Athar Lina Initiative in Historic Cairo'. *The Journal of Public Space*, 6 (n. 1) (April 2021): 241–56 <https://doi.org/10.32891/jps.v6i1.1462>.

³Soto-Martin, Ovidia, et al., 'A Digital Reconstruction of a Historical Building and Virtual Reintegration of Mural Paintings to Create an Interactive and Immersive Experience in Virtual Reality', *Applied Sciences* 10, no. 2 (2020): 597. <https://doi.org/10.3390/app10020597>.

⁴Heritage is understood as a constant rethinking and redefinition cultural values by different agents—social groups, media, institutions, which are also constantly changing (Kolesnik, Rusanov, 2020, p.1).

management, drawing on examples from Egypt's Al Khalifa district and international initiatives (Figure 1).



Figure 1: Wings of Khalifa Mural.

Obstacles to Equitable Access

In historic districts like Cairo's Al Khalifa, residents frequently face displacement and exclusion from tourism and redevelopment, which favours outside interests. The area's rich built heritage (mosques, mausoleums) is coupled with a vibrant intangible culture (festivals, stories)⁵, but communal practices like the Mawlid of al-Sayyida Sukayna⁶, are often curtailed, undermining their role as placemakers. Similarly, in India's Shekhawati region, decaying nineteenth-century *haveli* murals are admired by tourists, but local communities see little benefit, contributing to neglect and damage⁷. These instances show heritage as contested terrain, where power determines which narratives are amplified and which communities are excluded.

Al Khalifa Murals

The Al Khalifa project, executed in collaboration with the Megawra Built Environment Collective, clearly demonstrates the capacity of AR murals to support community-centred heritage. Initial interventions near the Ahmad Bey Kohya Mosque involved painting four murals that combined local legends⁸ and scenes of daily life, which were subsequently activated via the Artivive app (Figure 2). The

⁵Arafa, Maram, 'Festivals as Catalysts for Spatial Transformation', *IASTE Working Paper Series* 313 (2020): 66–82.

⁶A religious festival celebrating the Muslim Saint al-Sayyeda Sukayna.

⁷Dawatwal, Priyanka, and Nirupama Singh, 'Digitization of Shekhawati Murals Using Augmented Reality Technology', *ShodhKosh: Journal of Visual and Performing Arts* 4, no. 2SE (2024): 247–55
<https://doi.org/10.29121/shodhkosh.v4.i2SE.2023.634>.

⁸The former British Empire by a British officer Robert Grenville Gayer Anderson, left an important contribution documenting the area's culture in the form of a book containing a retelling of the legends related to the area -

aim was to show that heritage belongs to residents and can be a source of pride and livelihood⁹. Feedback mixed enthusiasm and discomfort: some residents voiced discomfort with the focus on female figures¹⁰ or the monochrome palette—the project successfully engaged the community and highlighted intangible heritage. Building on this success, the participatory Wings of Khalifa mural (Figure 3) involved local teenagers in both the conceptualisation and painting phases¹¹. Its accessibility through both Artivive and Instagram encouraged social media sharing, demonstrating AR's motivational power for youth engagement and its role in fostering strong ownership while actively countering community tokenisation.

Maram Arafa's work on the Mawlid of al-Sayyida Sukayna illustrated the potential for preserving intangible heritage by using AR to virtually re-enact the discontinued *al-Zaffa*¹² procession, with content from songs and memories recorded by teenagers (Figure 4). This capability to revive practices that have vanished from public space and educate new generations about cultural traditions is also evident in global efforts, such as the digital reconstruction of seventh-century murals at China's Zhao Yigong Tomb using Adobe Aero, to document and reimagine the originals. Interplay of visual art, fashion, and ritual in Tang-dynasty burials emphasised the artwork's ritual significance and accessibility without endangering the originals¹³. In both contexts, AR becomes a bridge between tangible artefacts and intangible values¹⁴.

"The Legends of the Creatan Woman's House". These stories not only tell the legends passed on in the area since old times and told to Gayer Anderson by a Sheikh living in the house but also his own telling of how he came to be a custodian of the house. Gayer Anderson commissioned a contemporary local artist Abdel Aziz Abdu, from the area of Khalifa to create illustrations in the form of copper plates for each of the legends, leaving a beautiful testimony to the local folk art of his time and visual interpretation of the stories.

⁹Following Athar Lina's philosophy, "Athar Lina (The monument is ours) believes that only when cultural heritage is beneficial to the community, will the community become an active partner in its conservation" <https://atharlina.com/about/>

¹⁰The coffee-owner, however, was delighted. Amm Mustafa, a 60-something gruff man loved the drawing and his judgment proved to be sounder than ours. The women were not just accepted; they were appreciated and soon became a landmark that brought the coffee shop more business. It became common for strangers visiting the neighbourhood, for its many mawlid (saint day celebrations) for example, to meet at "the coffeeshop with the women". Ibrashi, *Heritage in the Street: Megawra* | BEC's Athar Lina Initiative in Historic Cairo, 245.

¹¹<https://www.tandemforculture.org/stories/al-khalifa-love-wings/>.

¹²After the outbreak of COVID-19, the Egyptian Authorities implemented precautionary measures to limit gatherings by canceling a number of activities, including *mawlids*. For two consecutive years, al-Khalifa did not witness the festivals of al-Khalifa. No one can predict how long the cancellation of *mawlids* will last, and if they will return. And if they return, it is unclear if they will have the same appearance, spatial effect, and rituals or whether they will change or be downsized (Arafa, 2020, p.74).

¹³Zheng Sun, 'Intangible Heritage Restoration of Damaged Tomb Murals Through Augmented Reality Technology: A Case Study of Zhao Yigong Tomb Murals in Tang Dynasty of China', 2024 <https://ssrn.com/abstract=4588557>.

¹⁴"While tangible heritage often gains more attention than intangible heritage in cultural protection, it is still imperative to acknowledge that intangible heritage complements and substantiates the historical, cultural and artistic context' (Zhen, 2024, p.1).



Figure 2: One of the AR murals in Al Khalifa and the AR view in ARTIVIVE on a mobile phone.



Figure 3: Implementation of the Wings of Khalifa mural with local youth.

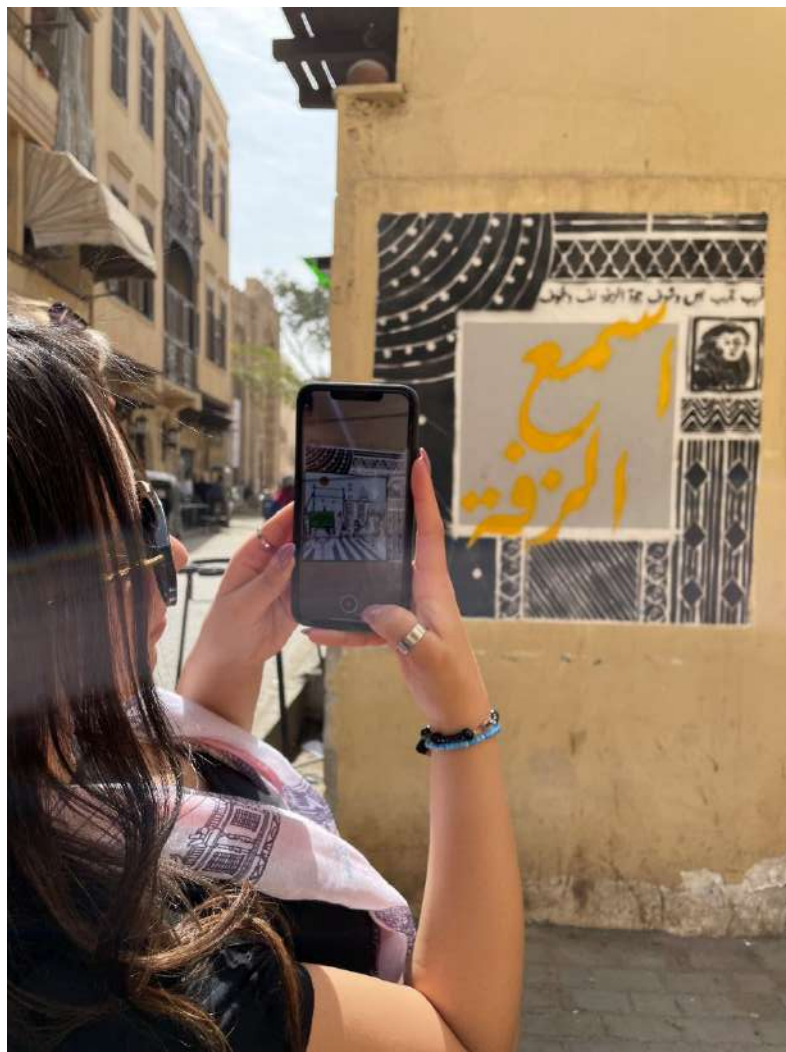


Figure 4: Mural marker for the Mawlid of al-Sayyida Sukayna's Zaffa experience.

Remembering and Reactivating

Beyond Cairo, AR is established as a tool for urban revitalisation and conservation, primarily through the capacity to reclaim and reactivate place. The Augmenting Angri project in Italy¹⁵ employed AR to digitally restore and tour 20 decaying murals, stimulating interest in neglected neighbourhoods and initiating dialogue on local identity, including contentious social issues like organised crime¹⁶. Similarly, the digitisation of the fragile Shekhawati murals in India, utilising open-source tools to create AR overlays, helps democratise access to this open-air gallery. This initiative highlights the efficacy of low-cost technologies in contributing to preservation and attracting donations for conservation, thereby offering a replicable model for cash-strapped communities globally¹⁷. Collectively, these diverse projects underscore AR's significant potential in education, conservation, and comparative research on mural traditions.

Ethical and Technical Imperatives for Sustainable AR

The effective and ethical deployment of AR in heritage requires rigorous consideration of both technical choices and ethical governance. Technical decisions fundamentally impact project sustainability, notably the ongoing shift from marker-based AR—which relies on physical tags and can be impractical on fragile surfaces, as observed in projects like Al Khalifa and Angri—to marker-less, geospatial approaches that utilise GPS and computer vision. Future research, such as Bauer et al.'s *Augmenting Murals*¹⁸, suggests that marker-less AR is achievable, thus eliminating the need for intrusive signage, a necessity in sensitive archaeological sites.

For long-term sustainable AR projects, one must simultaneously address critical ethical issues. Foremost is inclusive representation: projects must mandate the involvement of local stakeholders in content creation to ensure narratives accurately reflect their lived experiences and avoid exoticisation. Workshops like those run by Michalczyk and Arafa serve as successful models for amplifying marginalised voices. Relatedly, the ease of digital creation introduces the risk of low-quality replicas and misinformation, which can trivialise cultural assets¹⁹. Therefore, maintaining scholarly rigour demands a careful balance between creativity and accuracy, supported by transparent curation of sources. Critics also caution that excessive or entertainment-driven overlays turn historic sites into theme parks, undermining their cultural significance.

¹⁵Pagliano, Annachiara, 'Between Memory and Innovation: Murals in AR for Urban Requalification in Angri (SA)', In *Representation Challenges: New Frontiers of AR and AI Research for Cultural Heritage and Innovative Design*, edited by Unknown, (Conference Proceedings, 2023).

¹⁶Similarly as in the case of the Zaffa in Khalifa, in Angri young people were often unaware of very recent history, such as local hero General Gennaro Niglio's fight against the mafia (Pagliano, 2023, p.135).

¹⁷Their deterioration reflects not only environmental stress but also socioeconomic changes: many haveli owners migrated, leaving their houses unattended, (Dawatwal, Priyanka, and Nirupama Singh. 2024, p.248).

¹⁸Bauer, Alexander, Martin Kocur, and Josef Hagler, 'Augmenting Murals: Creating Playful AR Experiences for Wall Art Exhibitions', *8th IEEE VR Internal Workshop on Animation in Virtual and Augmented Environments*, IEEE, 2025.

¹⁹Soto-Martin, Ovidia, et al., 2020, p.3.

Beyond content, structural issues of digital equity must be addressed. Although commercial entities often promote AR as an engine for tourism, the expense of professional infrastructure and reliance on proprietary platforms create significant barriers for developing nations²⁰. Exclusive corporate projects risk widening digital divides and marginalising local voices in governance.

Consequently, exclusive corporate projects risk widening digital divides and actively marginalising local voices in governance. A further threat to sustainability is platform obsolescence: dependence on proprietary platforms (e.g., Meta's Spark AR, Adobe Aero) creates a critical vulnerability where their discontinuation²¹ results in the loss of AR experiences and their data. Since big tech companies often retain ownership of user content, this structural reality raises concerns over cultural sovereignty, necessitating that practitioners favour open-source or locally hosted solutions and advocate for protective regulations. Finally, ethical implementation requires strict moderation and contextual respect to prevent excessive, entertainment-driven overlays from transforming historic sites into themed environments, which would fundamentally undermine their cultural significance²².

Conclusion

AR murals offer an innovative fusion of visual art and digital storytelling for heritage preservation, enabling the visualisation of marginalised narratives and the creation of digital surrogates. To harness this potential, practitioners must couple technical ingenuity with ethical sensitivity, requiring them to center local voices, ensure accuracy and transparency, plan for platform obsolescence, and advocate for supportive legal frameworks.

This methodology respects the theoretical understanding that heritage is lived, not merely preserved in stone²³, as rituals and memories provide monuments with their meaning, allowing AR murals to weave narrative threads between physical and digital spaces.

Future development must therefore commit to addressing pressing issues: resolving technological challenges by implementing hybrid AR models in dense districts²⁴, assessing and mitigating the

²⁰BrandXR, 'AR Murals in Historic Preservation: Bringing the Past to Life', April 2025,

<https://www.brandxr.io/ar-murals-in-historic-preservation-bringing-the-past-to-life>.

²¹[https://spark.meta.com/blog/meta-spark-](https://spark.meta.com/blog/meta-spark-announcement/#:~:text=Following%20a%20thorough%20assessment%2C%20we,effective%20Tuesday%2C%20January%2014%2C%202025)

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[faq.html#:~:text=Adobe%20Aero%20will%20be%20discontinued,content%20until%20December%203%2C%202025](https://helpx.adobe.com/aero/aero-end-of-support-faq.html#:~:text=Adobe%20Aero%20will%20be%20discontinued,content%20until%20December%203%2C%202025).

²²Soto-Martin, Ovidia, et al., 2020, p.3.

²³Scholars such as Laurajane Smith argue that heritage is a cultural process involving negotiation and interpretation rather than a fixed set of objects, emphasising that tangible and intangible elements are inseparable: rituals, songs, and memories give meaning to monuments and public spaces, while built environments provide context for social practices.

Smith, Laurajane, *Uses of Heritage*, 1st ed. (Routledge, 2006) <https://doi.org/10.4324/9780203602263>.

²⁴As an example, an AR project displaying Islamic patterns in Imam el Shafei Mausoleum was initiated in 2021 but was abandoned due to weak internet and GPS.

environmental footprint of AR infrastructure, and conducting empirical studies to ensure accessibility for diverse demographic groups, including seniors and the disabled. Thoughtfully implemented, AR murals serve as powerful tools for equitable and integrated heritage management, moving decisively beyond mere digital spectacle.

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Chapter 55

Design for Emergency and Disaster Scenarios: Concepts that Serve Humanity

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Abstract

Industrial design can provide a valuable lens through which existing solutions or persistent problems can be questioned, reframed, and ultimately reimaged as innovations or high-impact incremental changes. There are few things more important than receiving timely care and treatment for emergency medical situations or search and rescue scenarios. Through appropriately designed products, services, and systems, it is possible to reach and attend to patients, victims, and vulnerable people efficiently and compassionately. Likewise, medical and rescue personnel can be equipped with the necessary means to carry out their tasks effectively and with minimal frustrations. This chapter discusses the rationale and outcomes of a student design project resulting in 47 concepts for emergency and disaster scenarios. Benefiting from inputs from professional medical and rescue personnel, the concepts give a glimpse into how humanity could serve itself better than current solutions. However, without follow-up commitments and investments in R&D and implementation, the best concepts will never achieve their impact potential. Accordingly, whilst the chapter underlines the value of knowledge and ideas generated through design, it also points out that stakeholders outside of design are essential collaborators within the wider innovation ecosystem. Furthermore, in the special arena of design for emergency and disaster scenarios, the paper proposes a new global design competition as one plausible route to help design concepts become reality, leveraging funding and expertise from NGOs, think tanks, and philanthropic investors.

Keywords: *Industrial Design, Emergencies, Disasters, R&D, Implementation*

Introduction

Humanity is challenged on a regular basis to respond to the occurrences and after-effects of emergency and disaster scenarios. These scenarios occur worldwide and give concern to all countries. Examples include natural disasters (huge losses of life, injuries, and devastation through earthquakes, wildfires, and floods), as well as recurrent day-to-day emergency medical situations. Türkiye is especially poignant as a case study for this paper: a country severely affected on a regular basis by all three of the mentioned natural disasters¹, whilst also being the authors' country of residence.

¹AFAD Turkish Republic Ministry of Interior Disaster and Emergency Management Presidency, "About Us," 2025. Accessed September 6, 2025 [<https://en.afad.gov.tr/about-us>].

Disaster and emergency planning/management is well established as both a practice and an academic field². In Türkiye, responsibility for these matters is overseen by the Disaster and Emergency Management Authority (AFAD), a government agency operating under the Ministry of Interior. After the country's severe earthquakes of February 2023, it was clear that disaster readiness and response dialogues amongst the media and academics were heavily centred on the roles of civil engineering, architecture, and city or regional planning. Industrial design, service design, and design thinking more generally rarely enter the discourse on Turkish natural disasters. Recent efforts have started to raise awareness amongst stakeholders of the benefits of including design in emergency and disaster solutions within Türkiye and globally^{3,4,5}. We expect similar situations in other countries.

Our chapter provides insights in two critical areas: (i) the value and power of educational design projects and design competitions to contribute creative and innovative solutions for emergency and disaster scenarios, and (ii) the responsibility of stakeholders other than designers to help turn the best of these solutions into impactful realities. We see the work as having relevance to all countries and parties committed to doing what they can to improve the situation of emergency scenario mitigation, preparedness, response, and recovery.

Industrial Design: A Journey of Change from Speculation to Reality

When design is effective, it leads to beneficial change⁶. Design provides an invaluable lens through which existing solutions or persistent problems may be questioned, reframed, and ultimately reimaged as innovations or high-impact incremental changes. Industrial designers focus on changes-for-the-better in the products, services, and systems that people can use: how they ought to be and how they can improve lives. This requires principles of user-centredness, to carefully consider and shape the experiences of people who will own, use, or interact with a designed solution. Successful solutions can deliver necessary functionalities, grab attention, deliver pleasing and comfortable experiences, and bring relevance and meaning. Moreover, designers must respect the demands for sustainable transition on environmental, social, and economic grounds⁷.

²David Alexander, *Principles of Emergency Planning and Management*, (Oxford: Oxford University Press, 2002).

³Sedef Süner-Pla-Cerdà, "Afet Yönetiminde Topluluk Katılımı: Bir Tasarım Çerçevesi Denemesi (Community Participation in Disaster Management: In Pursuit of a Framework for Design)," *Tasarım Kuram* 21, no. 44 (2025): 39–60.

⁴Owain Pedgley and Bahar Şener, "Natural Disaster Readiness and Response: Bringing Designers, Design Thinking, and Design Innovation into The Agenda," *She Ji: The Journal of Design, Economics, and Innovation* 10, no. 1 (2024): 120–138.

⁵Areli Avendano Franco, Liam Fennessy, and Judith Glover, "The Role of Industrial Design in Effective Post-Disaster Management," In Mitsutaka Matsumoto, Keiji Masui, Shinichi Fukushima, and Shinsuke Kondoh (Eds.), *Sustainability Through Innovation in Product Life Cycle Design*, (Singapore: Springer, 2017): 651–62.

⁶Donald Norman, *Design for a Better World: Meaningful, Sustainable, Humanity Centered*, (Cambridge: MIT Press, 2024).

⁷Michele Zannoni, et al., "Transitional Industrial Designer: The Responsibility of Designers and Companies for a Sustainable Transition," *AGATHÓN - International Journal of Architecture, Art and Design* 15 (2024): 332–343.

The act of designing provides a means of pushing the boundaries of existing knowledge about how the world is, and how it might alternatively be. Designers are necessarily researchers of current circumstances and creators of possible new futures. This holds independent of the sector of work, the complexity of the problem being tackled, or its tameness/wickedness⁸. Design brings excitement through new possibilities. At a high level of conception, designers reciprocate between a problem space (real, grounded, observed, investigated) and a solution space (imagined, modelled, predicted, foreseen, envisaged). Design solutions are inherently speculative until they can be tested, iterated, implemented, and evaluated.

METU Emergency Response Project

To understand how industrial design could contribute to solutions for emergency and disaster scenarios, we organised a term project in the third-year design studio at Middle East Technical University (METU), Ankara. An open brief was set in which the goal was ‘...to design a new or improved product and/or service for emergency response scenarios’. Students were expected to define their own project statement, dimensions, and priorities, relevant to the problem area they chose to work on. The class of approximately 100 students was divided into teams or individuals based on students’ preferences. Over the 8-week project, we benefited from input from professional and volunteer ambulance, medical, and rescue personnel, especially AKUT (Türkiye’s volunteer-based Search and Rescue Association). These personnel provided expertise, marketplace knowledge, and technical insights. At the final jury, we assessed 47 separate concept designs giving, a window into how humanity can serve itself better in emergency and disaster scenarios.

Analysis: What the Portfolio of Design Concepts Reveal

Disasters and emergencies are typically described with reference to various stages, such as the Design for Disaster Readiness and Response Framework⁹, which spans mitigation, preparedness, response I (self-help), response II (specialist / professional intervention), and recovery. We used the framework to analyse the content of the 47 concept designs, to determine the distribution of design effort made by students (Figure 1). Compared with the original framework, no concepts were generated within the ‘lighting’ sector but a new sector, ‘indoor and outdoor structures’ was created to contain several concepts that would otherwise be outside the framework. Cross-sectoral projects were placed in the sector to which they most strongly related. The analysis extended and validated the original framework. A total of 29 projects were in response II (specialist / professional intervention); 11 in response I (self-help); and 7 in stages either side of response, underlining our project interpretation of ‘response’ as the ‘designer’s response’ to emergencies and disasters. Regarding distribution across sectors, the results

⁸Ben Sweeting, “Tame Problems, Wicked Possibilities: Interpreting the Distinction between Wicked and Tame Problems through the Cybernetic Concepts of Variety and Constraint,” *She Ji: The Journal of Design, Economics, and Innovation* 10, no. 1 (2024): 32-52.

⁹Owain Pedgley and Bahar Şener, “Natural Disaster Readiness and Response,” 134.

were: medical first aid and emergency (15); automotive and vehicle (12); information services (5); indoor and outdoor structures (5); digital devices (4); personal protection (3); humanitarian (2); and medical rehabilitation (1). Although most design concepts were either related to first aid / medical assistance or transportation, the remaining were distributed across six other sectors, underlining our encouragement for creativity and a diverse portfolio of solutions.

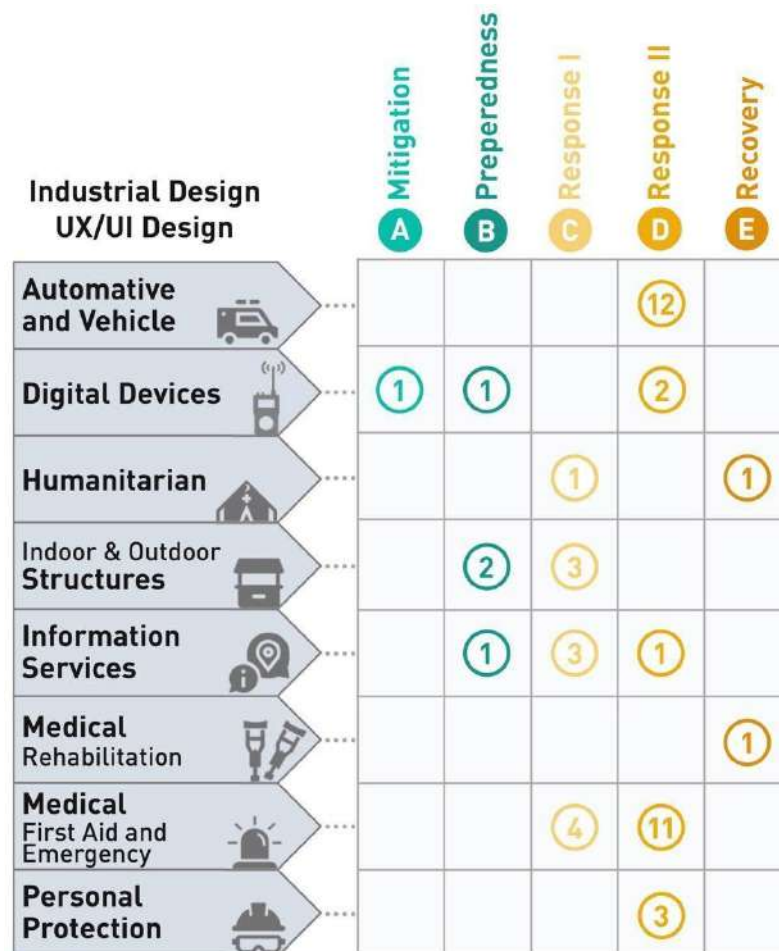


Figure 1: Projects mapped onto the design for disaster readiness and response framework.

Discussion

Amongst 47 student design concepts, the standard of design and persuasiveness varied. Many were good designs, but a relatively small number (~20%) could be seen to embody radical new thinking and directions (Figure 2). Typically, these highest quality solutions dealt especially well with human factors. For example, by focusing on ease of use under emergency and disaster conditions, minimal losses of time can occur between decision-making and actions. Medical and rescue personnel can be equipped with improved tools and better facilities to carry out their tasks more effectively and with reduced frustrations. Other strong concepts allowed victims, patients, and the vulnerable to be reached and attended more efficiently and compassionately.



Figure 2: Selection of projects embodying radical new thinking and directions: ‘Aura’ AI and AR powered device for automotive crash rescues (Aylin Aygün, Serhat Sorgusormaz); ‘Cervical Collar’ for use by a solo medic (Barış Arman Karakaş); ‘Side by Site for Pets’ emergency care shelter for rescued pets (Beste Toprak, Firuze Şenyurt, Betül Akkurt); ‘Aegis Core’ search and rescue helmet with integrated accessories (Aybüke Durmaz, Semina Çalışkan).

Beyond Design

There is never a shortage of ideas coming from an educational design project such as METU’s Emergency Response. The highest quality concept designs leave a very strong impression, communicated via advanced visualization, digital simulation, and physical mock-ups. Design concepts are impactful in that they get us thinking about how things and situations can be made better, and why it is that solutions do not already exist. But proposing and arguing a good design is only the start of a long journey. Turning a design into a reality that has impact on its intended users (and commercial impact if relevant too) requires activities beyond design. Conventionally it requires a transition into R&D, or to start-up/incubator support, which if successful can then attract the substantial financial investments necessary for implementation (Figure 3).

We should acknowledge that industrial designers and design students are not inherently entrepreneurial (they have other designs to get on with) and often lack the technical expertise to transition to R&D, although some individuals may be willing to take on such roles that extend beyond design. Usually, multidisciplinary collaborations are needed to turn conceptually sound ideas into physical or digital¹⁰ realities. In other words, although design may be the creative spark or the valuable precursor to innovation, design concepts must be nurtured and supported by other stakeholders if they are to have a chance of making genuine impact. Otherwise, even the most promising concepts will disappear into obscurity.

¹⁰Laura Giraldi, “Design for Emergency: A New Area of Development and Application,” *DIID Disegno Industriale Industrial Design* 77 (2022): 118.

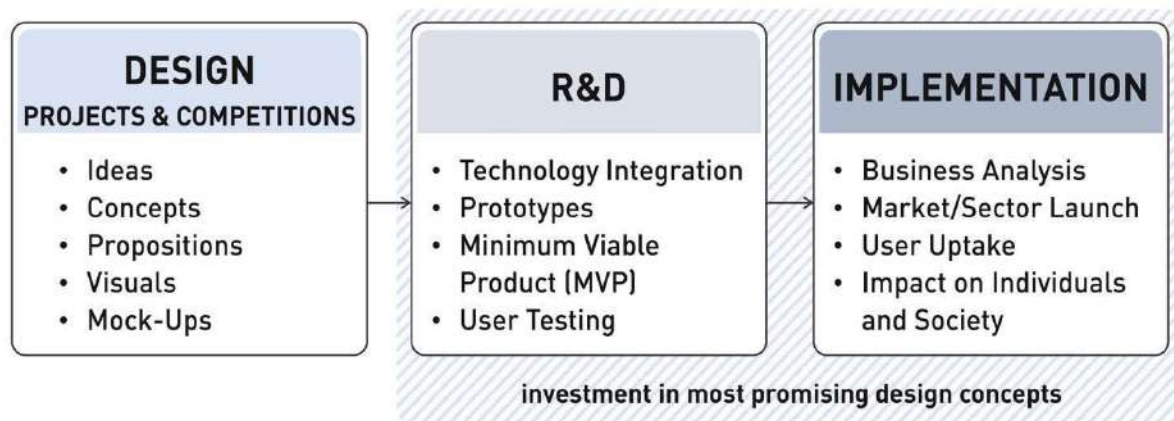


Figure 3: Design, R&D, and implementation as a continuum.

A New Global Design Competition?

Emergency and disaster solutions often function as insurance for potential crises rather than as regularly used products. This can make them difficult to conceive and develop under commercial design practice or have limited relevance for competitive marketplaces. However, emergencies and disasters seem fundamentally important to address for humanity and societal good. Solutions should be available without privilege or prejudice. New ways should be found to effectively engage governments, policymakers, think tanks, investors, private companies, NGOs, and the like to help turn new design concepts into reality. One plausible route could be to establish a new global student and professional design competition specifically for emergency and disaster scenarios. Designers of award-winning concepts may receive the most valuable prize: a commitment by the competition sponsors to organise and fund the transition of the concept through R&D and, if successful, implementation stages.

Conclusions

The work in this chapter has sought to underline the value of design as a creative and integrative discipline that draws upon technological and scientific breakthroughs as well as its own disciplinary principles of user-centredness. Designers can contribute substantially to solutions for emergency and disaster scenarios. However, a lack of follow-on collaboration, opportunities, or investment to elevate the technology readiness level of design concepts should not be an acceptable excuse for outstanding ideas failing to be realized and achieving an impact.

Acknowledgements

This chapter is dedicated to the personnel of Ankara AKUT who tragically lost their lives whilst tackling the wildfires in Eskişehir and Afyonkarahisar districts of Türkiye in July 2025: Bayram Eren Aslan, Alperen Özcan, Tekin Enes Sarıyıldız, Muharrem Can, and İlker Onarıcı. Our project could not have been a success without the expertise and enthusiasm of Ankara AKUT's input. We must also thank all students and our full-time and part-time instructor colleagues (Evren Akar, Ece Yalım, Yaz Erciyas, Mert Kulaksız, Açelya Küçükçukurt, Mehmet Erdi Özgürlük) for their commitment and effort on the project.

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Chapter 56

Back to the Future: Exploring the Untapped Potential of Freehand Weaving

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Abstract

This chapter presents a speculative, practice-based body of research investigating indigenous weaving, one of the earliest forms of architectural technology, as a material practice of architecture rather than a decorative one. Focusing on freehand weaving traditions from the Middle East and North Africa (MENA), the study explores how ancestral techniques can be reimagined for contemporary architectural design, in ways that support cultural continuity, socio-economic opportunity, and environmentally responsive making.

The research proposes repositioning the artisan as a central figure in the design and construction process—one who operates across scales, from object to space, in collaboration with architects and designers. It asks whether the same techniques and hands used to weave baskets might be extended toward the construction of space, and what architectural possibilities emerge through such a shift. The study argues that sustainable futures may lie in reviving overlooked, environmentally sensitive, and contextually specific techniques rooted in indigenous traditions.

Material collaborations with a multi-generational family of Egyptian weavers investigate the translation of basket-weaving techniques into architectural applications. Through experiential, auto-ethnographic research, and cycles of creative production, this chapter demonstrates how design can elevate craft by expanding its applications and reinforcing the knowledge embedded within traditional practices. By cultivating exchanges between designers and artisans, this research positions freehand weaving as a viable, living material technology for contemporary architectural design.

Keywords: *Indigenous Weaving, Ancestral Intelligence, Ancestral Technology, Artisanal Architecture, Craft-based Design*

Introduction

Weaving is among the earliest technologies developed by humankind^{1,2}, with deep historical roots in utilitarian function, cultural expression, and spatial innovation. Knowledge embedded in weaving has been transmitted across generations through embodied practice, shaping both material artefacts and

¹Edward A. Jolie et al., “Cordage, Textiles, and the Late Pleistocene Peopling of the Andes,” *Current Anthropology* 52, no. 3 (June 2011): 285–96; Jiří Svoboda et al., “Palaeolithic Textiles and Basketry Impressions from Dolní Věstonice,” in *The Dolní Věstonice Studies*, vol. 4, ed. Petr Škrdla (Brno: Institute of Archaeology, 2005).

²Jolie et al., “Cordage, Textiles”; Svoboda et al., “Palaeolithic Textiles and Basketry.”

the social structures that sustain craft traditions. Initially used for basketry, shelter, and textiles, weaving technologies became foundational to construction and social organisation³.

The artisan embodies an ancestral intelligence transmitted through the hands, the oldest human tools.⁴ Through sustained engagement with natural materials and environmental conditions, craftspeople developed making practices that were materially efficient and environmentally responsive. The work of Egyptian architect Hassan Fathy demonstrates the architectural potential of such relationships. In projects such as the *Village of New Gurna* (1948) and the *New Baris Market* (1967), Fathy collaborated with skilled earth masons to produce affordable, climatically responsive architecture rooted in local material culture⁵. However, industrialisation has progressively distanced society from material knowledge and making, marginalising many artisanal practices.

This research argues that sustainable futures in architecture and design may lie in the reactivation and evolution of overlooked, environmentally sensitive, and contextually specific ancestral practices rather than in entirely new inventions. It proposes reintegrating the artisan into contemporary design practice by advancing indigenous freehand weaving traditions, particularly those native to the MENA region, and translating them into spatial design as the basis for a culturally rooted, materially intelligent, and environmentally responsible architectural language.

Materials and Methodology: Closed-circle Technology

Khoos is a freehand weaving practice using dried palm fronds, widely practiced across the MENA region and rooted in Bedouin and coastal communities⁶. Closely tied to the date palm, a tree central to sustenance in arid environments, khoos employs locally available, unprocessed plant fibres that are abundant, renewable, biodegradable, and inexpensive. Practiced without tools, the technique relies solely on the hands, coiling split palm leaves around a core of rice or oat grass through an additive process. Form emerges directly through the act of weaving, producing inherently three-dimensional structures in which process and product are inseparable. Rooted in local ecological rhythms, khoos requires minimal resources, leaves no waste, and remains widely accessible, operating as a closed-circle material technology. Its spatial logic, the capacity to generate structure, surface, and volume from a single material system, offers a compelling framework for sustainable architectural exploration.

Khoos also holds cultural significance as a form of intergenerational knowledge, traditionally transmitted through women in many Gulf communities⁷. Its material properties provide shade and ventilation, making it climatically responsive and well-suited to hot and arid environments. Harvested

³Erik Andersson Strand et al., “Textiles, Cordage and Basketry from Çatalhöyük,” in *The Matter of Çatalhöyük: Reports from the 2009–2017 Seasons*, ed. Ian Hodder (Ankara: British Institute at Ankara, 2021).

⁴Richard Sennett, *The Craftsman* (New Haven: Yale University Press, 2008).

⁵James Steele, *The Hassan Fathy Collection: A Catalogue of Visual Documents at the Aga Khan Award for Architecture* (Singapore: Concept Media, 1997).

⁶Peter Vine, *Traditional Crafts of Saudi Arabia* (London: Stacey International, 1986), 43–47.

⁷UNESCO, “Date Palm, Knowledge, Skills, Traditions and Practices” <https://ich.unesco.org/en/RL/date-palm-knowledge-skills-traditions-and-practices-01902>.

from date palm waste without damaging the tree, the craft aligns with natural cycles of renewal and supports environmentally sensitive modes of making.

The research methodology is grounded in practice-based, auto-ethnographic inquiry through sustained collaboration with a multi-generational family of Egyptian weavers. Central to this work is Laila Mohammed Saeed, an experienced Upper Egypt khoos weaver who learned the craft from her mother and has transmitted it to her daughters. The research unfolds through episodic cycles of hands-on material experimentation, critical reflection, and creative production. Analogue weaving experiments are documented and translated into digital three-dimensional models, which are further developed into modular systems and construction typologies capable of defining space. This hybrid analogue–digital workflow enables the investigation of khoos as a scalable material technology, demonstrating its potential to produce robust, volumetric forms and spatial surfaces through both modular and in-situ architectural applications (Figure 1 and Figure 2).



Figure 1: Material experimentation and prototyping with khoos in collaboration with weaver, Laila Mohammed Saeed (Credit: Tania Ursomarzo).

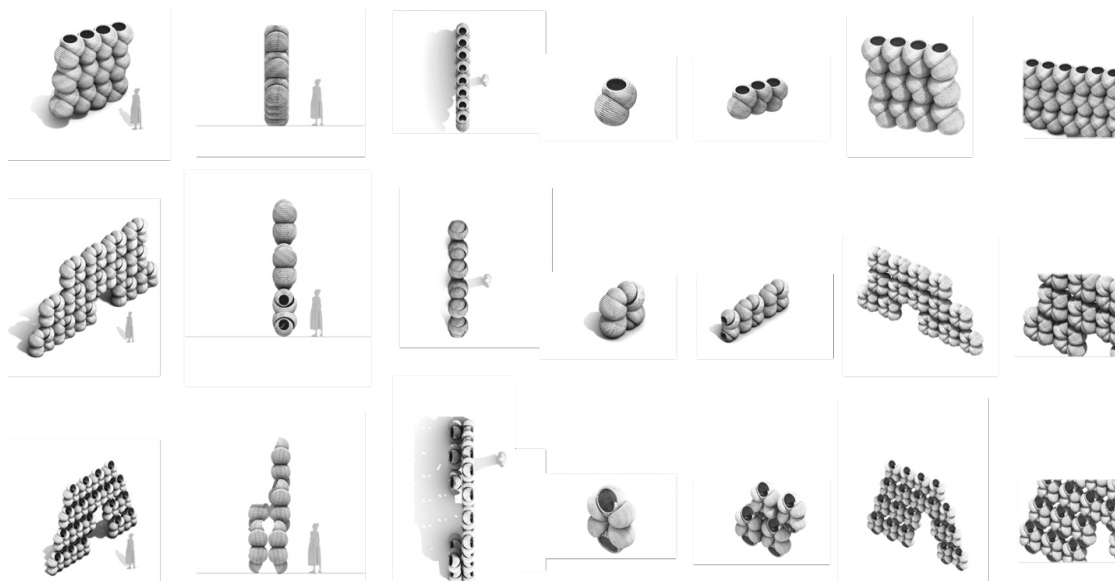


Figure 2: Digital translation and evolution of handwoven prototypes in three-dimensional model to study modular spatial assemblies (Credit: Tania Ursomarzo).

The Contemporary Position of Indigenous Weaving

Despite the continued presence and practice of indigenous weaving across North Africa, the skills of highly knowledgeable craftspeople remain underutilised in contemporary contexts. Their work is primarily directed towards the production of decorative objects destined for export to home furnishing markets abroad or for sale in local tourist economies. In some instances, foreign merchants have facilitated wholesale contracts with international retailers, enabling artisans to secure broader distribution of their work⁸. While such arrangements provide valuable economic opportunities for remote craft communities, they also generate a dependence on external markets and the success of foreign businesses. Moreover, the products created for export are typically limited in type, design, and function, often differing only in colour or surface pattern, resulting in minimal diversification of the craft⁹ (Figure 3).

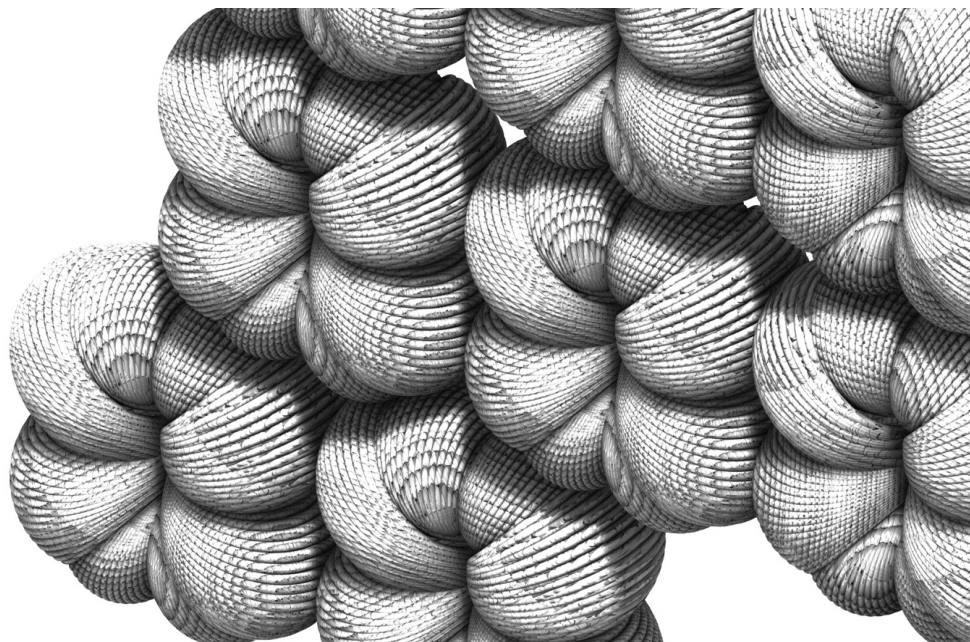


Figure 3: Detail of a digitally evolved prototype exploring a modular spatial assembly (Credit: Tania Ursomarzo).

From Function to Ornament: The Changing Role of Craft

The manner in which woven objects are presented in international markets has contributed to a significant shift in their cultural perception. Handwoven baskets and bowls, for example, are marketed and displayed as wall-mounted or shelf-based décor, categorised within store offerings as ‘decorative’ accessories rather than as functional items of daily use¹⁰. This practice distances the artefacts from their utilitarian origins, reframing them as exotic commodities defined by geographic and cultural otherness. Historically, craft has been understood as the production of objects whose artistry lies in the mastery of

⁸Kanju Interiors, “Woven Baskets,” accessed August 2, 2025 <https://kanjuinteriors.com/collections/woven-baskets>.

⁹Baskets of Africa, “Zimbabwe Masterweave Binga Bowls,” accessed August 2, 2025 <https://basketsof africa.com/product-category/masterweave-binga-bowls/>.

¹⁰SAFFRON + POE, “Art and Décor,” accessed August 2, 2025 <https://saffronandpoe.com/collections/decor>.

skill and the functionality of the final product¹¹. By this definition, the specialised fabrication techniques employed in weaving should be recognised as a form of advanced technology, comparable to industrial processes, capable of producing both utilitarian and aesthetically rich outcomes. Today, however, craft is often reduced to ornament.

Stagnation, Technological Resistance, and the Need for Innovation

While many weavers possess a sophisticated repertoire of techniques, their application has been largely confined to a narrow range of products with limited evolution over time. Rather than advancing towards new forms or markets, the practice of freehand weaving has focused on continuity and refinement of ancestral skill. An examination of products created by artisans such as Laila and her family reveals minimal differentiation or formal innovation; the woven goods they produce today closely resemble those made by preceding generations. This continuity is further reinforced by a broader cultural resistance to integrating new weaving technologies into traditional practices. As Soliman et al. observe, contemporary weaving in Egypt still adheres to ancient processes, with many craftspeople reluctant to experiment with technological adaptation¹². This lack of progression perpetuates the perception of craft as an outdated or irrelevant technology, diminishing both its economic value and its potential to contribute to contemporary design and architecture.

Repositioning Indigenous Weaving as a Contemporary Design Technology

Expanding artisanal production beyond traditional objects enables craft to be repositioned as a relevant and adaptable design technology capable of addressing contemporary challenges. This shift creates opportunities for meaningful collaboration between designers and artisans, with design operating as a tool to cultivate traditional processes, extend their applications, and build upon the artisan's technical expertise.

Advancing woven handicraft into product and spatial design generates new economic opportunities while transforming the role of the artisan. Craftspeople traditionally engaged in small-scale production can also participate in the fabrication of spatial systems and architectural elements, operating as specialised collaborators alongside designers, architects, and builders across scales. Reframing woven processes as technology rather than product positions craft as a versatile contemporary method of making. The advancement of weaving as a modern material technology supports the emergence of a regionally rooted architectural language and construction methodology, situating craft as both cultural heritage and an active agent in contemporary design production.

¹¹Lucy Donkin, *Crafts and Conservation: Synthesis Report for ICCROM*, Version 1.0 (Rome: International Centre for the Study of the Preservation and Restoration of Cultural Property, February 2024), 5–6.

¹²Dalia Soliman, Gamal El-Din Abdel Razeq, and Youmna Zaki, "Spinning and Weaving as Ancient Egyptian Inherited Crafts," *Pharos International Journal of Tourism and Hospitality* 1, no. 2 (2023): 18–32.

Conclusions: Design Futures Informed by Ancestral Knowledge

The marginalisation of craft within contemporary design discourse has contributed to the perception of handmaking as static or irrelevant. This research challenges that view by demonstrating that indigenous weaving practices, when critically and collaboratively engaged, possess significant potential to inform sustainable, locally grounded architectural solutions. Woven handcraft must be repositioned as a purposeful, forward-looking practice that is economically viable, technically relevant, and culturally resonant.

Integrating ancestral technologies into contemporary design requires approaches that respect their origins while enabling adaptation to new contexts and demands. Design plays a critical mediating role in this process, creating new applications, markets, and modes of transmission for artisanal knowledge. Through such exchanges, traditional practices can be translated into architectural strategies capable of addressing pressing challenges, including material scarcity, climate responsiveness, and social equity. Ultimately, this research proposes that sustainable design futures depend not solely on new technologies but on the reactivation and evolution of ancient knowledge systems, where tradition and innovation operate as mutually generative forces shaping a more sustainable and equitable built environment.

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Professor Naren Barfield is an internationally recognised academic and research leader with more than 20 years of senior executive leadership experience. He was an inaugural Council Member and Insight and Engagement Champion for Research England, and is a Trustee of LAMDA. As Deputy Vice-Chancellor and Provost at the Royal College of Art in London, he oversaw the academic, research and international portfolios, sustaining an unbroken QS World #1 ranking for 10 consecutive years, championing innovation through the integration of science, technology, arts and humanities, and establishing partnerships with universities in Japan, China, Singapore and the USA, including co-establishing one of the world's first international research laboratories in artificial intelligence and design with a leading Hong Kong university.

Over his career he has produced more than 100 publications, keynote speeches and conference presentations to parliamentary groups, science councils and learned societies, additionally with more than 90 individual and collaborative exhibitions in the UK, Europe, USA, South Africa, Australia, China and Japan, with creative work included in collections worldwide including the Victoria and Albert Museum, the British Museum, and collections in the USA, Japan and China.

Professor Barfield's grant capture exceeds eight figures (> £10m) as PI or CoI, and he has served nationally and internationally across research councils and funding bodies as peer reviewer, strategic advisor, or chairing key sector funding and review panels. He continues to provide confidential consultancy to global advisory firms, cultural organisations, research bodies and universities on research strategy and assessment, digital infrastructure, quality assurance, student recruitment, and strategic planning.

He is a distinguished visiting professor at several international universities, a judge for the QS Reimagine Education Awards, an international jury member for the Frontier Design Prize, and has overseen over two dozen research degree supervisory completions or examinations in design, digital visualisation, motion graphics, fine art, drawing and psychology, cultural policy, education and pedagogy, virtual reality, curating, and machine learning.

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Part I

Wellbeing and Health Futures

Equira™ (VoxelPHITS): Democratising Precision Radiopharmaceutical Therapy for Global Cancer Care

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Dr Basri Johan Jeet Abdullah is a consultant interventional radiologist with over 30 years of clinical and academic experience. He is currently affiliated with PICASO Hospital and the University of Malaya Specialist Centre (UMSC) in Kuala Lumpur, Malaysia. He also serves as an Adjunct Professor at Taylor's University and is a Retired Professor from the Faculty of Medicine, University of Malaya.

Dr Basri specialises in interventional radiology and biomedical imaging, with expanding interests in PET/-CT imaging and radioligand therapy. His expertise includes advanced image-guided procedures, vascular and oncologic interventions, and prostate imaging. A committed innovator, he holds several patents, some successfully commercialised. He is also an active contributor to professional education through forums, workshops, and webinars. His extensive experience in radiological practices has established him as a leading figure in interventional radiology in Malaysia.

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Plasma Polymerized Nanoparticles: From Cell Imaging to Cancer Therapy

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Professor Behnam Akhavan is an Australian Research Council (ARC) DECRA Fellow and an Associate Professor of Biomedical Engineering at the University of Newcastle, Australia. He leads the Plasma Bio-engineering Laboratory at the School of Engineering and the Hunter Medical Research Institute (HMRI). Since obtaining his PhD in Advanced Manufacturing from the University of South Australia in 2015, he has held postdoctoral and academic positions at the Max Planck Institute for Polymer Research and Fraunhofer Institute of Microtechnology in Germany, and the University of Sydney. Prof Akhavan's pioneering work in plasma bioengineering, published in over 90 journal articles, has led to innovative applications in healthcare and beyond. He is recognised by Engineers Australia as one of the nation's Most Innovative Engineers.

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An Affordable Brainwave Reader to Help People with Motor Neurone Disease (MND) Communicate via Thoughts Using Novel AI Technology

Amin Al-Habaibeh

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Professor Amin Al-Habaibeh is a leading academic and currently serves as Professor and Chair of Intelligent Engineering Systems within the Product Design team at Nottingham Trent University (NTU). His pioneering research is reshaping the future by making a tangible, positive impact on individuals, communities, and society at large.

Professor Al-Habaibeh has held several prestigious leadership roles, including UK National Director of the Doctoral Training Alliance in Energy (DTA- Energy). He acts as the Director of the Product Innovation Centre at NTU.

With more than 26 years of experience in industrial research and collaboration, and 8 years as an industrial placement adviser, he maintains strong and dynamic ties with industry.

An accomplished scholar, Professor Al-Habaibeh has authored over 240 international publications and patents. His work has gained widespread recognition, featured by major media outlets including CNN, BBC, The Daily Telegraph, Al Jazeera, The Guardian, The Sun, and The Daily Mail.

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IA Multimodal Platform for Objective Pain Measurement

Yacine Hadjiat

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Dr Yacine Hadjiat, MD, PhD, is a physician and healthcare innovator specialising in pain, neuroscience, advanced healthcare technologies, public health, and health system transformation. He currently serves as the Head of Innovation in Health Science and Digital Health at Dubai Health, and is an Associate Professor of Innovation at the Mohammed Bin Rashid University of Medicine and Health Sciences (MBRU) in Dubai. Dr Yacine Hadjiat holds several international academic collaborations and affiliations, including with INSERM (Institut National de la Santé et de la Recherche Médicale), Université Paris Cité, ESCP Business School, and other global institutions. His career spans clinical practice, academic research, and executive leadership roles across the life sciences sector in Europe, the United States, Asia, and more recently, the Middle East.

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A Low-cost, Portable, and AI-powered Device for Cardiac Investigation

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Dr Ernest Nlandu Kamavuako received his Master's and PhD in Biomedical Engineering from Aalborg University, Denmark, in 2006 and 2010, where he served as Assistant Professor (2010-2014) and Associate Professor (2014-2017) in the Department of Health Science and Technology. He joined King's College London as Senior Lecturer in the Department of Engineering in October 2017. From 2012 to 2013, he was a Visiting Postdoctoral Fellow at the Institute of Biomedical Engineering. Between 2017 and 2021, he was appointed Adjunct Professor in the Department of ECE, University of New Brunswick, Canada. He was an Academic Visitor in the Department of Bioengineering at Imperial College London, United Kingdom, in 2017. He has a strong publication record. His research focuses on cardiac disease diagnosis and fluid intake monitoring, with a particular emphasis on low-income settings. He is now an Associate Editor for Frontiers in Neuroscience, Neuroprosthetics section.

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Edge AI-enabled Smart Glasses and Companion Robots for In-home Health Monitoring and Medication Adherence

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Professor Michele Magno is currently a Senior Researcher and Privatdozenten at ETH Zürich, Switzerland at the Department of Information Technology and Electrical Engineering (D-ITET). He is head of the D-ITET Centre for Project-based Learning at ETH (pbl.ee.ethz.ch). He received his master's and PhD degrees in electronic engineering from the University of Bologna, Italy, in 2004 and 2010, respectively. He was a postdoctoral researcher at Tyndall Institute, Ireland and University College Cork, Ireland, and a visiting professor at University of Nice and ENSSAT University of Rennes, France. His current research interests include smart sensing, low-power machine learning, wireless sensor networks, wearable devices, energy harvesting, low-power management techniques, and extension of the lifetime of battery-operated devices. He has authored over 350 papers in international journals and conferences, with some publications awarded as best paper awards in the IEEE International Conference on E-health Networking, Application and Services 2018, IEEE Sensors Applications Symposium (SAS) 2018, IEEE International Workshop on Advances in Sensors and Interfaces 2017, among others. He is a senior IEEE member and an ACM member.

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Transforming Preeclampsia Care Through Cross-disciplinary Innovation: From Platelet Biomarkers to Real-time Clinical Decision Support

Patricia Maguire

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Professor Patricia Maguire is a leading interdisciplinary scientist known for merging AI with Biomedical Science. She is a Professor of Biochemistry at University College Dublin (UCD) and serves as Director of the UCD Institute for Discovery, an interdisciplinary research institute focused on addressing global challenges.

Professor Maguire's pioneering work on the 'platelet releasate' has advanced the understanding of platelet biology. She utilises this knowledge to develop novel diagnostic and therapeutic strategies for inflammatory diseases, including multiple sclerosis, venous thromboembolism, and pre-eclampsia, and leads the multi-award-winning AI_PREMie, a UNESCO Global Top 100 AI Project. Her research has earned her numerous awards, collaborations with major industry, and over 70 peer-reviewed articles in prestigious journals like Nature Communications, PNAS, and Blood. She enjoys teaching and is a vocal advocate for women in STEM, with an award-winning commitment to equality, diversity, and inclusion.

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MONA: A Robotic Patient Simulator for Occupational Therapists Training

Perla Maiolino

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Professor Maiolino is a leading expert in soft robotics and tactile sensing, serving as Associate Professor at the University of Oxford and is a senior member of the Oxford Robotics Institute. She founded the Soft Robotics Lab. Her research and innovations, such as CySkin, have led her to leadership roles in major partnerships like the SESTOSENSO project and the EPSRC 'From Sensing to Collaboration' grant, as well as keynote talks, awards, including the Queen's Anniversary Prize, features on the BBC, interviews with the Wall Street Journal and Computerphile, and exhibitions at the Science Museum in London. Her team's work on origami robotics was selected for the 2024 Prototypes for Humanity Exhibition in Dubai and showcased at the British Science Festival. Besides her research, she contributes as an Associate Editor for top journals like SoRo and RA-L and founded the Women in Robotics at ORI, promoting diversity and inclusion within the robotics community.

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PCAD: Prosthetic Comfort by Design–An Educational Innovation in Prosthetic Measurement

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Dr Anthony McGarry is a Senior Teaching Fellow within the Department of Biomedical Engineering at the University of Strathclyde and a Health and Care Professions Council registered prosthetist and orthotist. He plays a central role in the delivery and development of both undergraduate and postgraduate education with a particular focus on lower limb prosthetics. His teaching integrates clinical expertise with research-informed practice to support the development of competent and reflective healthcare professionals.

Dr McGarry completed his doctoral studies at the University of Strathclyde in 2009, where his research evaluated prosthetic shape capture systems. This work established a foundation for his continued interest in improving the accuracy and effectiveness of prosthetic design processes. His research expertise centres on clinical management strategies alongside socket design methodologies, shape capture techniques, and the assessment of residual limb interface pressures.

His current research activity focuses on the evaluation of prosthetic shape capture methods and the application of computer-aided design technologies in prosthetics. Through this work, he contributes to advancing evidence-based practice and enhancing patient outcomes. Dr McGarry has published in peer-reviewed journals and continues to engage in collaborative research that bridges clinical application and engineering innovation within prosthetics and orthotics.

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Artificial Intelligence and Quantum Computing for the Design of Novel Kisspeptin-10 Analogues and Their Experimental Evaluation in Cervical Cancer Cells

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Dr Deisy Yurley Rodríguez-Sarmiento is a Full Professor at the Universidad Autónoma de Bucaramanga (UNAB) in Bucaramanga, Colombia. She obtained her PhD in Biochemistry from the University of São Paulo, Brazil, where she specialised in peptide design, molecular pharmacology, and GPCR signaling. Her research focuses on the rational design, synthesis, and experimental evaluation of peptide-based ligands aimed at modulating G protein-coupled receptors (GPCRs), with particular interest in biased agonism, receptor structural dynamics, and the development of innovative therapeutic candidates.

Throughout her career, Dr Rodríguez-Sarmiento has led interdisciplinary projects involving chemical peptide synthesis, molecular modeling, functional assays (including BRET-based signaling), and structure–activity relationship analysis. She has contributed to advancing the understanding of GPCR-mediated signaling pathways in cancer and other pathological conditions, and her work integrates

computational approaches with experimental validation to accelerate the discovery of targeted peptide modulators.

In addition to her research activities, she teaches courses in biochemistry, pharmacology, and molecular biology, and actively mentors undergraduate and graduate students.

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PermeaSense: Rethinking How We Test Antimicrobials in the Fight Against Biofilm Infections

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Dr Eleonora Secchi is Group Leader at ETH Zurich, where she leads the bioMatter Microfluidics group. Her research focuses on the physics of biofilms—bacterial communities with major implications in medicine and the environment—investigating their structure, mechanics, and resilience through microfluidics, soft matter physics, and biophysics. Trained in soft matter physics during her PhD at Politecnico di Milano, she later specialised in nanofluidics during a postdoc at ENS Paris, where she authored a Nature paper.

In 2018, she was awarded the prestigious SNSF PRIMA Grant to establish her own research group at ETH Zurich. Her work has since produced high-impact publications and a patented microfluidic platform for probing antibiotic tolerance in biofilms. Recognised as a Soft Matter Emerging Investigator in 2022, she also serves on the ESA Topical Team on Biofilms and contributes to the international committees of several leading conferences in soft matter and porous media.

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Nano Plants (Nanostructured Implants)

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Professor Bala Vaidhyanathan is a Professor of Advanced Materials and Processing and was the Associate Dean for Enterprise at Loughborough University (LU). He leads the Advanced Ceramics Research Group and Loughborough Materials Characterisation Centre, a £10 million state-of-the-art facility, in the Materials Department. He has authored over 200 publications (>5280 citations, H-index 40), 7 book chapters, is an inventor on 17 patents, and delivered >60 plenary, keynote, and invited presentations in international conferences. He is also the Chief Editor of *Advances in Applied Ceramics* and on the Editorial Board for four international journals. He holds >47 research grants worth >£30.5M, of which 40 had direct industrial contributions.

Vaidhyanathan has pioneered the development of field-assisted sintering methods for functional ceramics, and Loughborough is currently regarded as one of the world leaders in the utilisation of these

techniques and hosts the largest additive manufacturing (AM) ceramics group in the UK. He is also the University's Special Envoy for Internationalisation.

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Part II

Sustainable and Resilient Infrastructure

Co-creating Cities with AI and Digital Twins: A Multispecies Participatory Approach

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Professor Andrea Conserva is an urban innovation expert, European project manager, and researcher with over a decade of experience at the intersection of advanced architecture, sustainable urban transformation, and digital technologies. Based in Barcelona, Andrea currently contributes to international R&D projects within the Advanced Architecture Group at IAAC and has previously worked at the CIRCE Foundation.

He has been involved in more than 20 publicly funded European projects (FP7, Horizon 2020, Horizon Europe), acting as project manager and coordinator in complex, multi-partner international consortia. His experience spans the full project lifecycle, from proposal development and strategic framing to implementation, coordination, and impact delivery.

His profile combines technical expertise in building energy modelling, simulation, and sustainability assessment with strategic roles in urban regeneration, nature-based solutions, participatory co-design, and digital innovation. He focuses on advancing participatory, data-informed urban design through Digital Twins, artificial intelligence, and gamification, supporting more resilient and inclusive urban environments.

Andrea has worked across public and private research ecosystems, developing strong skills in innovation management, stakeholder engagement, and interdisciplinary leadership. He has also contributed to capacity-building as a teacher, thesis advisor, and consultant, supporting training initiatives for public and private organisations.

He holds an MSc in Architectural Engineering from Politecnico di Milano and has completed academic programmes at the University of Mons, TU Wien, and Universidad Politécnica de Madrid. He is currently a PhD candidate at the University of Genoa, focusing on digital co-design tools for urban innovation and regeneration.

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ThermoChroma-smart Colorimetric Sensors as Cold Chain Indicators

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Dr Ahu Gümrah Dumanli-Parry is a University Lecturer (Associate Prof) in Bioinspired Soft Matter and the first recipient of the bp-ICAM Kathleen Lonsdale Research Fellowship. Dr Dumanli-Parry's research group (Bio-inspired Functional Materials-BioFuM- <https://www.biofumlab.com>) focuses on understanding the self-assembly process in nature as well as mimicking it to produce structurally ordered materials. With her research group, Dr Dumanli-Parry investigates the complex relationship between the intrinsic properties of the colloidal building blocks and the physical effects that modulate the self-assembly process to build active matter for sensing technologies and shape-morphing systems, as well as light-harvesting applications. She obtained her PhD from Sabanci University, Istanbul, and was a postdoctoral fellow at the University of Cambridge and Adolphe Merkle Institute in Switzerland. She was a teaching fellow in Advanced Characterisation of Materials at Imperial College London before taking up her role in Manchester.

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Reengineering Ancient Materials for Durable, Low-carbon Structures

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Professor Anwar Khitab is a researcher in sustainable and green construction materials, with a special focus on the analysis of ancient Indus Valley civilisation building techniques to derive eco-friendly solutions for modern use. His research promotes the integration of natural and carbon-negative materials into contemporary construction practices, aiming to reduce environmental impact and support long-term sustainability.

With over 100 research publications and two books authored, Professor Khitab has contributed significantly to the academic and practical advancement of sustainable engineering. He plays an active role in national engineering curriculum reforms and accreditation processes in alignment with international standards. As a keynote speaker and academic mentor, he advocates for sustainable construction and has supervised numerous postgraduate scholars. Beyond academia, he serves on advisory boards of several think tanks to promote research-driven, outcome-based education systems across Pakistan.

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Designing and Verifying Computational Models for Human-agent Teamwork in Future Cities

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Dr Alexandros Konios is an Assistant Professor in Cyber Security at Nottingham Trent University. He obtained his PhD in Computer Science and MSc in Computer Security and Resilience from the University of Newcastle upon Tyne (UK). He also holds a BSc in Computer Science from the University of Piraeus (Greece). He is a Fellow of Higher Education Academy, and a member of the British Computer Society and other professional bodies. Alexandros' core research interests centre on the analysis of interactive and concurrent systems, including both the theoretical aspects of their semantics and the application of formal techniques to the modelling and verification of such systems. Further research interests include model checking and temporal logic, data analysis, analysis of network protocols, design, usability analysis, and prototyping of interactive interfaces, behavioural analysis of activities of daily living in smart environments, AI and machine learning, Internet of Things (IoT), and cryptography.

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Multifunctional Hybrid Hierarchical Composites

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Dr Patrick C. Lee is an Associate Professor in the Department of Mechanical and Industrial Engineering at the University of Toronto. He received his B.Sc. from the University of British Columbia and his M.Sc. and Ph.D. from the University of Toronto, followed by postdoctoral research at the University of Minnesota. He began his career at The Dow Chemical Company as a Research Scientist and later served as Assistant Professor at the University of Vermont before returning to Toronto in 2018. Dr Lee's research focuses on polymer processing and characterisation, particularly processing–structure–property relationships in hybrid nanocomposites and polymer foams. He has authored over 110 journal articles, 160 conference papers, six book chapters, and holds 32 patent applications. He has led numerous government-and industry-funded projects and received several honours, including the CSME G.H. Duggan Medal (2020), NSF CAREER Award (2018), and PPS Morand Lambla Award (2018).

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Building Health: Resilient Building Materials for Global Health and Sustainability

Elizabeth L. McCormick

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Dr Elizabeth L. McCormick is a licensed architect, educator, and researcher at the University of North Carolina Charlotte. Her work explores climatically responsive design strategies that promote health and

reduce reliance on mechanical conditioning. Her recent book, *Inside OUT: Human Health and the Air-Conditioning Era* (Routledge), examines the social and technological forces behind conditioned indoor environments and advocates for healthier, more connected alternatives. Liz leads an NSF-funded study abroad program in Tanzania focused on sustainable housing and public health. She is a WELL and LEED.

Accredited Professional, a Certified Passive House Consultant, and has over a decade of architectural practice experience spanning single-family passive houses to LEED-certified commercial projects. Liz holds a PhD in Design from NC State University, an MS in Building Technology from the Massachusetts Institute of Technology, and dual bachelor's degrees from the Rhode Island School of Design.

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AeroFeathers: Biomimetic Propellers with 3D-printed Flexible Fibres for Quieter Drones

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Dr Bhisham Sharma is an Associate Professor in the Department of Mechanical and Aerospace Engineering at Michigan Tech and Director of the Mechanics, Acoustics, and Dynamics Laboratory. Dr Sharma's research vision is driven by a commitment to making engineering structures safer, quieter, and more efficient. His innovative research program is built upon creating new knowledge and overcoming technological challenges at the intersection of structural mechanics, dynamics, and acoustics. His group conducts pioneering studies on novel engineered material systems—including acoustic metamaterials, phononic structures, architected lattice structures, and stochastic foams—leveraging these insights to develop practical, performance-tailored solutions for critical engineering challenges across multiple industries. Dr Sharma also serves as Chair of the Structural Acoustics Technical Committee for the Institute of Noise Control Engineering (INCE), USA, reflecting his national leadership and impactful contributions to the field.

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Part III

Artificial Intelligence and Augmented Intelligence

Digital Twins of the Retina: A Computational Framework for Personalised Microvascular Health Assessment

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Dr Wahbi K. El-Bouri works at the cutting-edge of Digital Twin development as a Senior Lecturer (Associate Professor) at the University of Liverpool. With over 12 years of experience, he heads up his research team, the Virtual Vascular Human research group, where he develops Digital Twin technology of the vascular system.

An engineer by training, he received both his MEng and DPhil in biomedical engineering from the University of Oxford before transitioning to the Department of Cardiovascular Medicine in Liverpool to begin the process of translating these Digital Twins to clinical environments. Digital Twins that have been developed include simulations of stroke and its treatment, simulations of ageing retinas, and the dynamics of the heart. He has been funded by the European Union, the Royal Society, and UK research councils to continue to develop these healthcare Digital Twins. He also works as an advisor to two med-tech startups.

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The Internet of Beings: The Nightmares and Dreams of Digitalising Human Bodies

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Professor Francesco Grillo teaches the Master of Transformative Sustainability at Bocconi University (jointly held with Politecnico di Milano) and is a Visiting Fellow at the European University Institute. He is an Affiliate Professor at Scuola Superiore Sant'Anna of Pisa and teacher at the summer school of University of International Business Economics in Beijing. He has also been a Visiting Fellow at the Oxford Internet Institute and at St. Antony's College (University of Oxford).

Grillo is the Director of the think tank Vision, through which he leads two annual international conference; The future of Europe, and Global Governance of Climate Change– which acts as a problem solving platform gathering policy makers, academics, journalist and entrepreneurs from different countries and backgrounds. A third conference on "SKILLS FOR THE AI WORLD" is being planned for 2026 and the Middle East is considered a possible location.

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Augmenting Human Empathy: AI-assisted Solutions for Cross-cultural Healthcare Communication

Jeremy Howick

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Professor Howick is the Director of the Stoneygate Centre for Empathic Healthcare. Previously, he worked at the University of Oxford and co-founded the Oxford Empathy Programme. He holds degrees from Dartmouth College, the London School of Economics, and the University of Oxford. He is currently a member of the Sigma Xi honours society and recently founded the Global Network for Empathy in Healthcare.

With over 250 peer-reviewed publications and three books, including the Amazon #1 bestseller, he is a recognised authority. His work has earned awards from the British Medical Association, European Society for Person-Centred Care, and the University of Oxford. Professor Howick has appeared on the BBC, ITV, and NPR. He regularly speaks at high-profile events, delivering keynote lectures and workshops for corporations, NGOs, and academic audiences, inspiring change in healthcare practices worldwide. Outside of academia, he is an international rowing champion with a Commonwealth Games Silver Medal.

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Baseline Evaluation for Enhancing Human–Robot Collaboration (HRC) in Industry 5.0 Manufacturing

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Dr Erick Ramírez-Cedillo, PhD in Engineering Sciences, is a leader in advanced manufacturing and transformative education at Tecnológico de Monterrey, Mexico. As Director of the Innovation and Transformation Engineering Program, he bridges academia and industry. Co-founder of CUSTOMED (3DMA) and 3D FACTORY MX, Erick drives sustainable 3D printing solutions for rural and emergency settings. Leading the FrED Factory Lab with Massachusetts Institute of Technology, he advances Industry 5.0 and advanced manufacturing education.

With 39 publications, his research spans topology optimisation, digital fabrication, rapid prototyping, and smart manufacturing. His global impact includes a 2024 WUN Seed Funding Grant with the University of Sheffield and a UC Davis project for disaster relief. His 2020 ventilator, recognised by Mexico's government, addressed pandemic needs. A Level 1 member of Mexico's National Research System, Erick shapes engineering education, empowering communities through technology.

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An Integrated AR-FEM-AI System for Real-time Structural Simulations and X-ray Visualisation of Heritage and Ageing Buildings

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Dr Iasef Md Rian is an architect, academic, and researcher specialising in computational design, parametric structures and optimisation, performance-based architecture, and fractal-informed design. He is an Associate Professor and Research Officer in the Department of Architecture and Design at XJTLU since 2019. Previously, he was an Assistant Professor at the University of Sharjah, UAE, and earned his PhD from Politecnico di Torino, Italy, focusing on architectural computation and design systems.

He is actively involved in the Council of Architecture (India), IASS, ISGG, CAADRIA, and CAAD Futures and has conducted numerous design-build workshops, with student projects at Made Expo (Milan) and Dubai Design Week (Dubai). As a reviewer for top-tier journals, including *Automation in Construction*, *Frontiers of Architectural Research*, and *Computer-Aided Design*, Dr Rian contributes to advancing architectural scholarship. He is the founder of Rian Architects Designers in Malda, India, delivering residential and commercial designs.

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AI-driven XR Platform for Cognitive and Motor Empowerment in Young Students with Disabilities

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Professor Mario Covarrubias Rodriguez is an Associate Professor at the Department of Mechanical Engineering at Politecnico di Milano. He leads the Virtual Prototyping and Augmented Reality Lab at the Lecco Campus, where he focuses on the design and implementation of immersive technologies. His research explores the development of Extended Reality (XR) applications across diverse domains, including engineering education, special education, industrial training, physical rehabilitation, and cultural heritage preservation.

With a multidisciplinary approach, Professor Covarrubias combines technical innovation with user-centred design to create impactful XR solutions that enhance learning, accessibility, and user engagement. His work bridges academic research and real-world applications, contributing to advancements in digital transformation and inclusive technology.

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Revolutionising Filmmaking: Artificial Intelligence-driven Motion Control with the Cinema Camera Robot

Ishwar Singh

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Dr Ishwar Singh served as an Adjunct Professor at McMaster University's School of Engineering Practice and Technology (SEPT) from 2011 until his retirement in 2023. Before that, he had a distinguished career in teaching and administration at Mohawk College and became the founding Associate Director of the BTech McMaster/Mohawk programs, chairing the process automation program. He played a key role in securing over \$2 million to establish an automation centre and support degree programs.

At McMaster, he led curriculum design for automation, automotive, and biotechnology B.Tech programs and contributed to the energy engineering technology degree completion program. He managed the SEPT Learning Factory for Industry 4.0 education and research. Additionally, he helped establish M.Eng. programs in Systems and Technology, served as faculty lead for undergraduate and graduate projects, and was principal investigator for Future Skills Canada-funded smart systems initiatives. He has authored and coauthored more than 100 publications/presentations.

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Part IV

Environmental Sustainability and Climate Action

AI-optimized Green Hydrogen Production from Biomass and Wastewater, and Integrated CO₂ Capture Pathways via Solar-Fenton and Natural Catalysts

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Dr Shabib Sulaiman Al Rashdi is a Senior Lecturer and Head of the Waste-to-Energy Research Lab at the National University of Science and Technology, Oman. He holds a PhD in Chemical Engineering from the University of Kuala Lumpur. Dr Al Rashdi specialises in sustainable energy technologies, focusing on waste-to-energy conversion, green hydrogen production, and circular economy solutions aligned with Oman Vision 2040. Notably, he supervised a pioneering project that transforms palm waste into recyclable green aluminium, positioning Oman as a leader in zero-waste innovation. His research integrates renewable energy and advanced materials to address environmental challenges while promoting economic diversification.

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Integration of Deep Learning with CubeSat Technologies for Environmental Monitoring

Faris A. Almalki

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Professor Almalki is a Professor in Wireless Communications and Drones in the Computer Engineering Department at Taif University, a research fellow in the Department of Electronic and Computer Engineering at Brunel University of London, and a member of the IEEE Communication Society. He holds an MSc in Broadband and Mobile Communication Networks from Kent University and a PhD in Wireless Communication Networks from Brunel.

Professor Almalki is a reviewer for many respected journals and publishers, including Springer, IEEE, Elsevier, and Oxford University Press. His research interests include UAVs and Satellites and their wireless applications. Besides topics related to AI, IoMT, ML, he has also published over 100 research articles, 1 book, participated in 4 specialised books, and secured 3 research grants from the Deanship of Scientific Research. More notably, he has been a part of Stanford's global list of the top 2% of the world's scientists since 2022 and has received many best research awards at IEEE conferences.

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Simultaneous Selective Recovery of Lithium and Cobalt from Spent Lithium-ion Batteries Using Modified Bipolar Membrane Electrodialysis

Chosel P. Lawagon

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Dr Chosel P. Lawagon is the Director of the Centre of Green Nanotechnology Innovations for Environmental Solutions and the Institute of Emerging Technologies at the University of Mindanao. She co-founded the Nano Society of the Philippines, promoting the advancement of nanotechnology for sustainability. Dr Lawagon holds a Ph.D. in Chemical Engineering specialising in Materials Science and Engineering from Myongji University, South Korea, and completed postdoctoral fellowships at Chulalongkorn University (Thailand) and the University of Bayreuth (Germany). Her research focuses on nanotechnology-based solutions for sustainable energy, environmental remediation, and agriculture. In 2021, the German Federal Ministry of Education and Research recognised her with the Green Talents Award. She was also a national finalist for the 2024 ASEAN-US Science Prize for Women. As a Balik Scientist of the Philippines' Department of Science and Technology, Dr Lawagon leads interdisciplinary research, contributing patents and publications that address pressing environmental challenges in the Philippines and beyond.

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Advancing Circular Economy Through Ad-tech for Optimising Future Manufacturing

Chinaedu Maduagwu

Pratt Institute, United States of America

Professor Chinaedu (Chinos) is an Adjunct Professor at Pratt Institute's Creative Enterprise Leadership department, teaching in the Design Management and Arts and Cultural programs. He teaches various courses starting with Strategic Technology and Design Operations Management, where they explore sustainable ways of operations within organisations using strategic technology. He also teaches the Data Analytics part of the Financing companies and new ventures course and Finance for Nonprofit Managers, a course that lets creatives analyse objectives and performances of organisations and how best to promote sustainable practices. For over 5 years he served as a faculty fellow for Pratt Institute's collaboration with Made in NYC. As a facilitator and consultant, he worked with multiple local small business companies in the New York area to refine products and solutions that were value-centric to their customers. He also enjoys working with creatives and entrepreneurs to help them start and build businesses.

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Transesterification Optimization of Vhembe Macadamia Nuts Oil into Biodiesel Using Inorganic KOH Catalyst

Mamookho Elizabeth Makhatha

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Professor Makhatha is a registered professional natural scientist (Pr.Sci.Nat-), rated by the South African National Research Foundation (NRF), and a Full Professor at the Metallurgy Department, Faculty of Engineering and the Built Environment, University of Johannesburg (UJ). She is a Physical Chemist with a PhD in Polymer Science. Professor Makhatha is now Head of School (HoS): School of Mining, Metallurgy and Chemical Engineering at UJ.

Her research explores how biodegradable plastics can socially contribute to a more sustainable economy and influence consumer behaviour towards eco-friendly products. She prepares, characterises materials (polymers and alloys), and adjusts parameters for different applications that need smart/advanced and environmentally friendly materials for high performance and a sustainable future. She is an inspirational leader, passionate about knowledge dissemination, enjoys mentoring early career researchers, and enjoys planting the seed as well as lifting others up. Her current head of school position focuses on leading cross-disciplinary research initiatives.

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SEAWEED FOAM: A Bio-foam Material for a New Type of Home-compostable Packaging Products

Austėja Platūkytė

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Professor Austėja Platūkytė is a material-design researcher and educator working at the nexus of design, science, technology, and craft. A doctoral candidate in Design at Vilnius Academy of Arts, she lectures on Biomaterial Design while investigating hybrid living materials. As founder of SEAWEED FOAM, she developed an algae-based bio-foam for home-compostable packaging, advancing Lithuania's circular-economy agenda. A pioneer of material design and zero-waste philosophy in Lithuania, she established the Biomaterials Library—the Baltic region's first sustainable-materials collection—and leads the NGO Medžiagotyra to promote zero-waste principles. Her symbiomimicry-driven practice produces symbiotic objects showcased at Milan Design Week, Dutch Design Week, and MaterialDistrict Utrecht. She has presented research at Cumulus Detroit, IEEE ICTE, MaterialDistrict Utrecht, and the EUSBSR Forum. A multi-year Lithuanian Council for Culture scholarship recipient and Green Concept Award nominee, Platūkytė collaborates with academia and industry to accelerate sustainable innovation.

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Transforming Agricultural and Plant-based Byproducts into Compostable Hygiene Materials for a Circular Economy

Rashmi Prakash

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Professor Rashmi Prakash is a biomedical engineer and adjunct professor at the University of British Columbia (UBC), where she teaches in the Faculty of Applied Science in the School of Biomedical Engineering with a focus on sustainability, circular design, and equity in engineering. With a background in medical device research and materials innovation, her work explores the intersection of environmental health, women's health, and regenerative material systems. Rashmi's research includes developing compostable fibres from agricultural waste for use in hygiene, packaging, and hydroponics. Her research-informed innovation has received multiple national and international awards, including recognition from the MaRS Women in Cleantech Challenge and Octane Medical Innovation Forum. She is passionate about applying academic R&D to address global challenges.

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Using Hydrokinetic Energy for Green Hydrogen and Green Oxygen Production

Patrick H. Rice

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Dr Patrick H. Rice is the Chief Science and Research Officer at the College of the Florida Keys. He is the Principal Investigator for several National Science Foundation research and education projects focused on training the 21st-century science and technology workforce. He is also the Vice President and Senior Marine Biologist for SharkDefense Technologies, LLC., an R&D company exploring shark repellent technology, which has been featured on the Discovery Channel - Shark Week, Animal Planet, BBC, National Geographic, PBS, and NOVA. Dr Rice has 15 peer-reviewed scientific publications on a variety of marine science disciplines, including marine biology/biochemistry, fisheries science, and marine aquaculture. He has a Ph.D. in Marine Biology and Fisheries from the Rosenstiel School of Marine and Atmospheric Science, University of Miami, a Master's degree in Wildlife and Fisheries Science from Texas A&M University, and a Bachelor of Science degree in Aquatic Biology from the University of Texas– Austin. From 1994-1997, he was a United States Peace Corps Volunteer in South Pacific Islands of Fiji, providing protein to indigenous people through aquaculture education.

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Mixed Waste Plastics Derived Composites for Flood and Hurricane Protection

Dipa Ray

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Professor Dipa Ray is a leading academic in the field of polymer composites with over 24 years of experience. She has published 100 papers in peer-reviewed journals, 14 book chapters, edited a peer-reviewed journal, and holds one patent.

She has over 7000 citations, an H-index of 43, and an i-10 index of 93. She is one of the recipients of Top 50 Women in Engineering awards in the UK in 2021. She is a Fellow of IOM3 (FIMMM) and the Royal Society of Chemistry (FRSC).

Dipa Ray is a member of the IOM3 Sustainability Group, Board Member of the Natural Materials Association (NMA, IOM3), and serves in the editorial boards of the Plastics, Rubber and Composites Journal and the Journal of Reinforced Plastics and Composites. She received the Young Scientist Award from the Department of Science and Technology (DST) and the Career Award for Young Teachers from All India Council for Technical Education (AICTE) from the Government of India in 2008.

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Leveraging AI-coupled Digital Twin Ecosystems for all Sustainable Development Goals in the Built Environment

Noha Saleeb

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Dr Saleeb is an Associate Professor in Creative Digital Technologies and Construction, and Programme Leader for MSc Building Information Modelling Management programmes, providing consultation for industry projects/organisations in sustainable design, construction, digital transformation, BIM, Digital Twins, AI, and onsite project management.

She is Director and Business Development Lead-BIMAfrica, Editor-in-Chief of the Smart Infrastructure and Construction Journal, and advisory board member of several Professional Body steering committees e.g., London Digital Twin Research Centre, BIM4Heritage, CIOB Innovation SIG. Dr Saleeb has also delivered many keynote/plenary speeches globally and has >100 journal/conference/industry/book chapter publications in sustainable construction technologies. She is co-author of the Chartered Institute of Building (CIOB)-UK 'Artificial Intelligence Playbook', and 'Digital Twins Position Paper for AECO' by the National Institute of Building Sciences, USA. She achieved multiple national and international awards, most recently Green Gown UK/Ireland Sustainability Champion Award 2024.

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Part V

Socio-economic Empowerment and Innovation

Tools2Thrive: A Scalable Tool Rental Model for Smallholder Farmers in Kenya

John Gershenson

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Dr John Gershenson is the Director of the Humanitarian Engineering and Social Entrepreneurship Program (HESE) at Penn State University. He is also CEO of Kijenzi, a Kenyan company using distributed digital manufacturing to democratise local manufacturing in Sub-Saharan Africa. Dr Gershenson has a B.A. in Physics from Cornell University, an M.S. in Mechanical Engineering from the Ohio State University, and a PhD in Mechanical Engineering from the University of Idaho.

Dr Gershenson's research in product/process architecture, lean/sustainable design and manufacturing, and appropriate technologies have yielded 100+ peer-reviewed publications and commensurate research funding. He has strong experience in developing technologies and their applications in Kenya, having led another company prior and helped several others launch, including those through Penn State's HESE program, which has launched six social impact companies in the last 4 years.

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The Second Act of Life: Unveiling Podcast Narratives of Purpose and Reinvention Among Midlife Entrepreneurs

Katherina Kuschel

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Dr Katherina Kuschel, Ph.D., is a researcher and Director of Research Funding at Centrum Graduate Business School and the Pontificia Universidad Católica del Perú. She also teaches Technology Entrepreneurship and Research in Entrepreneurship at the Karlsruhe Institute of Technology (KIT) in Germany. Her work focuses on entrepreneurship, entrepreneurial ecosystems, and gender dynamics, with particular emphasis on women in technology ventures and women in STEM in Latin America.

Dr Kuschel has led and coordinated multiple international research projects. These include an applied research project funded by the ASPEN Network of Development Entrepreneurs and the International Development Research Centre (IDRC), aimed at developing entrepreneurial solutions in clean energy, as well as a project funded by the German Academic Exchange Service (DAAD) and the 2021 KIT International Excellence Fellowship on university soft-landing programs for foreign startups. Her research combines perspectives from entrepreneurship, business management, social psychology, and regional economic development.

She has co-edited a Routledge volume on wellbeing and women entrepreneurs and has published extensively in leading academic journals in the fields of entrepreneurship and management. Her work contributes both to theoretical advancement and to the design of evidence-based policies and programs supporting inclusive entrepreneurial ecosystems.

In 2025, Dr Kuschel was awarded the VIWA Outstanding Researcher on Women's Entrepreneurship, recognising her interdisciplinary contributions and sustained impact on research and practice in entrepreneurship.

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The Re-habitualisation of Boycotts: From Disruption to Everyday Life

Wang-Shu Liu

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Ms Wang-Shu Liu is a postgraduate researcher based in the Sociology Department and the Sustainable Consumption Institute at the University of Manchester.

She began her academic journey at the University of Nottingham Ningbo China, where she earned a bachelor's degree in finance and management. During this time, she developed an initial interest in sustainability, particularly in the areas of sustainable finance, corporate resistance, and business sustainability. This led her to pursue a master's degree in Sociology at the University of Manchester, where she shifted her focus to the consumer's perspective, exploring sustainability through the lens of everyday life practices.

Her research interests lie broadly in the fields of sustainable consumption, everyday life, and individual resistance, with a particular emphasis on how ordinary consumers engage with and contribute to social and environmental change.

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Eco-efficient Valorisation of Spent Yeast: Protein and β -Glucan Fractions Recovery for Health-promoting Applications

Joelle Nader

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Dr Joelle Nader is a distinguished scholar and innovator at the forefront of industrial process engineering, sustainable manufacturing, and technological advancement. With over a decade of experience spanning academia, research, and industry collaboration, her work bridges emerging technologies, operations management, and circular economy practices to advance human and environmental well-being. She has authored peer-reviewed articles, secured patents, and led globally recognised, award-winning, innovative projects. At the Lebanese American University, she directs cross-disciplinary initiatives, integrating business and engineering perspectives to foster agile, sustainable solutions for complex industrial systems. She frequently presents at international conferences and collaborates with industry partners on process optimisation and sustainable product development. Her current work explores AI-integrated production systems, smart automation, and advanced value chains, with a particular focus on food, pharmaceutical, and chemical industries. Dr Nader serves on advisory boards and champions science-led development across the MENA region.

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Innovative Invasive Cactus Management: A Sustainable Solution for Kenya's Rangelands

Willis Owino

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Professor Willis is a distinguished scholar in Food Systems research, with over 20 years of combined academic and industry expertise. His work explores the intersection of Food and Nutritional Sciences and Animal Sciences, aiming to enhance sustainable food production while minimising environmental impact—particularly for pastoralist farmers in Kenya's semi-arid regions. His research includes efficient feed systems and long-term food security solutions.

A prolific researcher, he has secured funding for projects from leading global donors, including USAID, World Bank (KAPAP, KCSAP), RUFORUM, BMBF, BLE, DFG (Germany), Rockefeller Foundation, BioInnovate Africa (SIDA-funded), JSPS Japan, GCRF-UK, DANIDA, ERASMUS+, Kenya-France PHC Partnership, and dryGrow Foundation (Italy). He has supervised 37 Master's and 11 PhD graduates and authored 125 peer-reviewed articles, five book chapters with internationally recognised publishers, and

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Next-generation Community Hubs for Socio-economic Empowerment: A Pilot Human-centred Framework and Participatory Digital Twin Approach

Alejandro Lozano Robledo

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Professor Alejandro Lozano Robledo is Director of the Future Mobility Design Lab at the University of Cincinnati, where he leads cutting-edge research at the intersection of human-centred design, technology, and social innovation. With over a decade of experience across academia and industry, Alejandro has collaborated with global organisations including NASA, the U.S. Department of Transportation, Boeing, Hyundai, and MIT.

His work focuses on creating transformative solutions that address access to mobility, healthcare, education, and employment, using technologies such as Digital Twins, AR/VR, and UX/UI. Alejandro has secured significant funding for high community impact research and innovation, earned eight U.S. patents, and mentored more than 400 students, integrating industry partnerships into the academic sphere. His projects span the U.S., Latin America, Europe, Africa, and Asia, advancing global innovation through multi-sectoral collaborations.

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Weaving Economic Dignity: A Framework for Re-engineering Value with Botswana's Heritage Basketry Artisans

Keiphe Setlhatlhanyo

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Dr Keiphe Nani Setlhatlhanyo is a Lecturer in Design at the University of Botswana, specialising in cross-disciplinary design research. Her work integrates design and craft heritage with community development, focusing on culturally significant products. She holds a PhD in Design (University of Leeds), where her research examined Botswana's culturally significant motifs, an MA in Product Design Innovation Management (Nottingham Trent University, Commonwealth Scholarship), and a Bachelor of Design (University of Botswana).

Dr Setlhatlhanyo actively collaborates with artisan communities, such as basket weavers, to improve designs and co-create solutions that enhance livelihoods. Involved in several funded research projects, she brings experience in product development, intellectual property, and project management. She has authored numerous peer-reviewed journal articles and book chapters.

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Part VI

Open

Beyond the Object: Product and Furniture Design as Critical and Social Practice

Jason Cleverly

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Dr Jason Cleverly is a designer, artist, and academic whose work explores how interaction, participation, and interpretation can be enriched through socially engaged design. His practice involves creating interactive installations for public and cultural spaces, using a variety of materials and embedded technologies to support inclusive and meaningful experiences. He often works collaboratively, using co-creative methods that value shared authorship and active participation.

Jason's work has been shown in a range of national and international exhibitions, highlighting the cross-disciplinary nature of his practice. His research has been published across fields including design, museology, and creative knowledge, contributing to wider discussions around affordances and the role of the artist-designer in socially responsive contexts. He is the Course Leader for BA Product and Furniture Design at the University of the Arts London, where his teaching is grounded in inclusive design principles and informed by ongoing research and critical practice.

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Prototype of the Sustainable Tourism Promotion Model Based on Technology 4.0 in Post-conflict Regions. Case Study: La Palma and Yacopí (Colombia)

Melva Inés Gómez-Caicedo

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Professor Melva Innes Gómez Caicedo is currently affiliated with the Los Libertadores University Foundation (Bogotá, Colombia) as an Associate Professor and consultant on research and organisational development for various institutions and companies. She is a Senior Researcher (ISr) according to the classification of the Ministry of Science, Technology and Innovation (Minciencias) and Leader of the Research Group on Economic, Administrative, and Accounting Reflection (REAC), which underscores her leadership in scientific production and her impact on the academic community. Her publications cover topics such as the impact of digital technologies on business competitiveness, the analysis of public transportation behavior in Latin America, sustainability, and business analytics approaches applied to artificial intelligence, contributing to the strengthening of institutional, academic, and research capacity. She is a PhD candidate in Public Management and Social Policy, with a Master's degree in General Management and a Bachelor's degree in Economics. She has led public and private projects related to tourism and agribusiness, combining her experience in applied research, high-impact academic production, and leadership in technological innovation and sustainable development projects. Her

career reflects a commitment to generating useful and replicable knowledge, geared towards solving real-world problems in local and global contexts.

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Study of Intergenerational Craft and Revival in Himalayan Communities

Gauri Karanjkar

MIT ADT University, India

Ms Gauri Karanjkar is an Assistant Professor at the MIT Institute of Design, ADT University in Pune. With a background in fashion design, she holds a B.Des from NIFT Mumbai and is currently pursuing a PhD in Art and Design. Her research explores the revival and sustainable growth of India's handloom and handicraft traditions, engaging with questions of cultural continuity, identity, and innovation within indigenous practices.

She is committed to bridging academic inquiry with grassroots narratives, aiming to foreground the voices and techniques of traditional artisans in contemporary discourse.

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Agentic AI for Sustainable Behaviour: A Coaching Framework and Workflow

Dario Krpan

London School of Economics and Political Science (LSE), United Kingdom

Dr Dario Krpan is an Associate Professor of Behavioural Science at LSE, where he is also affiliated with the LSE's Data Science Institute. He received his MPhil and PhD in psychology from the University of Cambridge. Doctor Krpan has strong expertise in a wide range of research methods, from experimental and quasi-experimental designs to predictive approaches such as machine learning. His research has been published in leading academic journals, including *Nature Human Behaviour*, *The Lancet Planetary Health*, and *Artificial Intelligence Review*.

Dario's primary research focus is on transformative behavioural change—specifically, how individuals can shift their lifestyles in response to major global challenges, such as climate change, and the societal impacts of technological transformation, including increased automation and the rise of artificial intelligence. Within this context, he also explores how AI and advanced technologies can be used to better understand and influence human behaviour.

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Eco-friendly and Biocompatible Materials for Noise Reduction in Healthcare Environments

Jesús Carbajo San Martín
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Dr Jesús Carbajo is an Associate Professor at the Department of Physics, Systems Engineering and Signal Theory of the University of Alicante in Spain, where he received his international PhD with cum Laude and Extraordinary Doctorate Award. His research activity is focused on the modelling, design, and characterisation of acoustic materials for noise-reduction applications. Over the last few years, he has participated as a Principal Investigator and researcher on multiple public and private projects.

He has also performed research stays in prestigious world-renowned institutions such as the Massachusetts Institute of Technology and Purdue University in the USA, the Institute of Sound and Vibration in the UK, and the Universidade de Coimbra in Portugal.

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Design for Change: Transformational Cross-cultural and Transdisciplinary Learning Experiences to Solve Global Healthcare Sustainability Challenges

Lisa Scharoun
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Professor Scharoun is a multi-award-winning teacher, researcher, and designer with expertise in visual communications with a focus on design for health and cross-cultural design. Lisa has received a number of national and international awards for her teaching and research, including the QS Wharton Re-imagine Education Global Award, the ACEEU Triple-E Award, and the Australian Awards for University Teaching. She has won many national and international prizes for her design work, including a top 10 finalist in the Bill and Melinda Gates 'Records for Life' competition.

She was also awarded the 'Ease of Adding Information' prize for a design solution created to assist mothers in developing countries to remember to vaccinate their children; a Good Design Australia Award for Social Design for her work on the Healthcare Excellence Accelerator (HEAL) project at QUT, and an A'Design Award for Strategic Design for her work on healthcare improvement in prisons.

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Part VII

Speculative

GameShift Futures: Reimagining the University Through Speculative Play

Livia Alexander

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Professor Livia Alexander is a Brooklyn-based curator, writer, and Associate Professor of Visual Studies at Montclair State University. Her work focuses on global perspectives in modern and contemporary visual art, cinema, and expanded media, with an emphasis on Southwest Asia and North Africa. She has curated exhibitions and programs at leading institutions, including MoMA, Tate Modern, and the Brooklyn Museum.

She currently curates the digital screens program at Moynihan Train Hall in New York and previously served as Chief Curator of the Film Criticism Forum launched by the Saudi Film Commission. She is the co-founder of ArteEast, a nonprofit supporting artist from the Middle East and North Africa. A Higher Education Academic Leadership Fellow and Visiting Scholar at the NYU Game Center, Alexander is developing an immersive game-based platform to rethink learning models in higher education.

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Prototypes of Personalisation and Customisation for Next-generation Medicines

Subham Banerjee

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Dr Subham Banerjee is an Associate Professor in the Department of Pharmaceutics, NIPER, Guwahati, India. He is also a Visiting Staff Faculty of the University of Texas (UT) at Austin, US. Due to his seminal contributions to the field of Pharmaceutical Additive Manufacturing (PAM), he featured in 'World Top 2% Scientist List' prepared by Stanford University, US.

Dr Banerjee has published more than 110+ peer-reviewed research articles with over 3000+ citations and an H-index of 31. He has 9 granted patents and has transferred 1 healthcare technology to the industry. Dr Banerjee has received several National and International competitive prestigious awards. He has successfully completed several Extramural Research (EMR) project grants funded by premium funding bodies in India. He has delivered 50+ invited talks at prestigious institutions worldwide. His pioneering work continues to shape the future of pharmaceutical 3D/4D printing, next-generation personalised medicine, and new materials exclusively for PAM.

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The Role of Design in Challenging Exclusionary Urban Spaces

Adrienne Bennie

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Dr Adrienne Bennie is a London-based designer, researcher, and educator whose work sits at the intersection of spatial justice, socially engaged practice, and critical design pedagogy. She is currently Senior Lecturer in Product and Furniture Design at University of the Arts London, where she leads Critical Practice within the BA (Hons) Product and Furniture Design programme.

Her research examines how design participates in systems of exclusion, with particular attention to hostile architecture and the material regulation of public space. Through interrogative, practice-led methods, their work explores how everyday urban objects shape access, behaviour, and belonging. Recent projects focus on critical making, digital fabrication, and pedagogical interventions as tools for exposing spatial inequality and generating public and professional debate.

Alongside their academic role, Adrienne contributes to cross-sector conversations across design education, policy, and civic contexts. Their work foregrounds ethical responsibility in the public realm and advances critical approaches to design that foreground ethical responsibility in the public realm.

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Gastroludology: Gastronomy Meets Ludology

Yoram Chisik

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Dr Yoram Chisik is a Senior Lecturer and Co-Program Lead of the MSc in User Experience (UX) Engineering at Goldsmiths, University of London. His work explores the ways in which people interact with technology and the means through which the physical and the digital can be woven together to create novel interactions and experiences. Yoram has over 30 years of experience in research, development, teaching, and consulting in both industry and academia across continents (Europe, Asia, and North America). Yoram has served as chair and editor for several academic conferences and journals in human-computer interaction and design. His work has been published in high-impact conferences, journals, and edited volumes. His most recent works explore the notion of playing with food, examining people's perceptions of electricity, investigating how people present themselves on social networks, and studying the adaptation of participatory design to working with children.

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From Walls to Worlds: Co-creating Heritage Narratives with AR Murals

Agnes Michalczyk

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Ms Agnes Michalczyk is a visual artist based in Cairo. She graduated from the Academy of Visual Arts in Leipzig, Germany in 2011. She teaches at the Faculty of Applied Sciences and Arts at the German University in Cairo and leads various art workshops. Her artwork explores the urban landscape of Cairo through a feminist lens. She employs a variety of media, contributing to numerous art projects both locally and internationally. Her recent endeavours explore immersive technologies in relation to urban heritage.

Michalczyk is pursuing her PhD research in the UNA Europa joint PhD program at Freie Universität Berlin and the University of Edinburgh.

Michalczyk is passionate about teaching art and design and introducing diverse artistic tools and techniques to her students. She aims to foster an open and inclusive space that encourages personal inquiry, experimentation, and creativity, meeting her students wherever they may be on their artistic journeys.

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Design for Emergency and Disaster Scenarios: Concepts that Serve Humanity

Owain Pedgley

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Professor Owain Pedgley is Professor of Industrial Design at Middle East Technical University (METU), Turkey. He received B.Sc. and Ph.D. degrees in industrial design from Loughborough University, UK in 1995 and 1999. His expertise and research centres on interfaces, interactions, and experiences, with special crossovers into materials and design, and musical instrument innovation. Owain is a long-time practitioner, supervisor, and advocate of research through design as an approach to academic research.

He is co-editor of the book series 'Materials Experience' (Elsevier, 2021; 2014) and was a founding member of the Industrial Design B.Eng. program at the University of Liverpool (2014-2017). Currently, he serves as Co-Director of UTEST Product Usability Test Unit at METU, as well as Design Director of Sonixpace, a new start-up developing wireless audio recording solutions. Prior to his academic career, Owain worked as a designer of sports equipment and musical instruments.

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Back to the Future: Exploring the Untapped Potential of Freehand Weaving

Tania Ursomarzo

American University of Sharjah, United Arab Emirates

Professor Tania Ursomarzo is an Assistant Professor of Architecture and Interior Design at the American University of Sharjah. She is an architect, multidisciplinary designer, and material fabrication specialist who works across various scales of design, from the urban to the artefact.

Professor Tania's interdisciplinary approach to creative practice centres on the design and fabrication of space and objects that explore the hybridisation of analogue and digital technologies using environmentally sensitive material processes. Tania holds degrees from the University of Toronto (BArch) and Cranbrook Academy of Art (MArch).

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