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 2050[1], resulting

[1]Falcon, 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 waste[2]. 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 sustainability[3]. 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 processes[4]. 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 products[5].

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 consumption[6]. 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.

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[2]Ezeorba, 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.

[3]Klai 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.

[4]Luzón-Quintana Luz María et al., "Biotechnological Processes in Fruit Vinegar Production," *Foods,* 10 no. 5 (2021): 945 https://doi.org/10.3390/foods10050945.

[5]Jaeger 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.

[6]Nader 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.

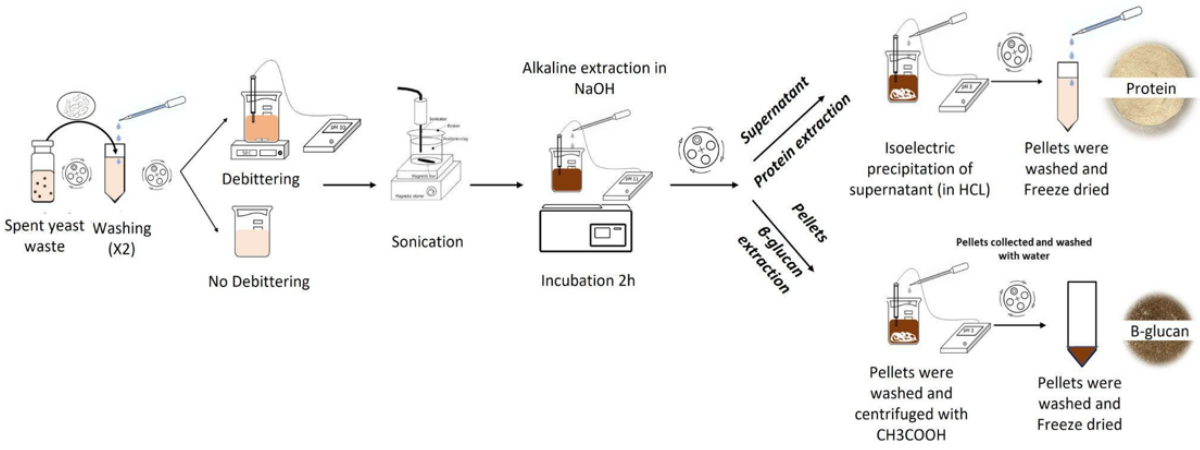

Figure 1: Schematic representation of the multi-step biomass fractionation of spent yeast waste into proteins and β-glucans.

Table 1: Chemical and biological composition of Protein and β-glucan-rich extract represented by (mean ± SD).

	Protein extract		β-glucan extract	
	PH	**PG**	**BA**	**BB**
Dry matter (%)	95.6±1	95.7±1.2	94.5±1.5	94.8±1.1
Ash content (%)	8.0±0.5	6.2±1.5	5.9±1	5.2±1.2
Protein content (%)	70.9±4.6	66.4±4.61	5±1.2	3.5±2.1
β-glucan content (%)	<1	<1	77.8± 2.6	62.7± 1.5
TPC (mg GAE/g DM)	28.5±0.6	24.9±0.4	12.2±0.1	12.8±0.3
DPPH (mg TE/g DM)	19.9±1.1	9.8±2.0	76.9 ±1.6	72.6 ±7.4
ABTS (mg TE/g DM)	33.5± 1.6	30.3± 1.6	97.6 ±3.5	89.4 ±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 ~180 kDa was seen corresponding to large protein aggregates. Faint bands at ~75 and ~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.

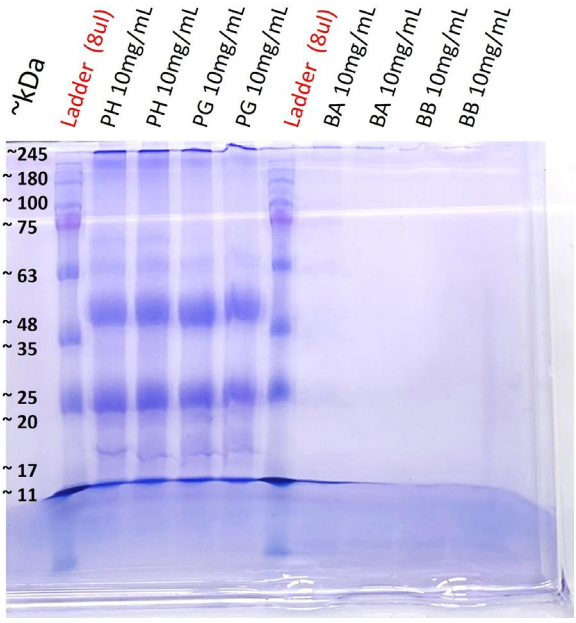

Figure 2: SDS-PAGE gel of the protein-rich extracts (10 mg/mL of PH and PG) and β-glucan-rich extracts (10 mg/mL of BA and BB) recovered from spent yeast.

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 ± 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.

	Protein extract		β-glucan extract	
Mineral	**PH (ppm ± SD)**	**PG (ppm ± SD)**	**BA (ppm ± SD)**	**BB (ppm ± SD)**
S	4402.0 ± 73.2	3840.3 ± 243.5	707.0 ± 48.5	512.7 ± 40.0
Ca	360.0 ± 43.6	757.0 ± 25.5	1417.3 ± 194.4	1270.3 ± 175.5
Fe	175.7 ± 4.5	68.7 ± 15.6	471.0 ± 5.0	471.7 ± 36.4
K	2388.3 ± 59.7	865.7 ± 25.5	76.3 ± 1.2	77.0 ± 0.8
Mn	34.7 ± 1.7	33.3 ± 0.9	33.3 ± 0.5	32.3 ± 0.5
Cu	14.0 ± 0.0	14.3 ± 0.2	18.0 ± 4.1	24.0 ± 2.2
Zn	36.0 ± 2.4	77.0 ± 3.7	13.0 ± 0.8	14.0 ± 3.6
Mo	13.0 ± 0.8	11.3 ± 0.5	9.3 ± 1.2	9.0 ± 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 alterations[7], 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 catalyse 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

[7]Lee 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 al[8]. 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.

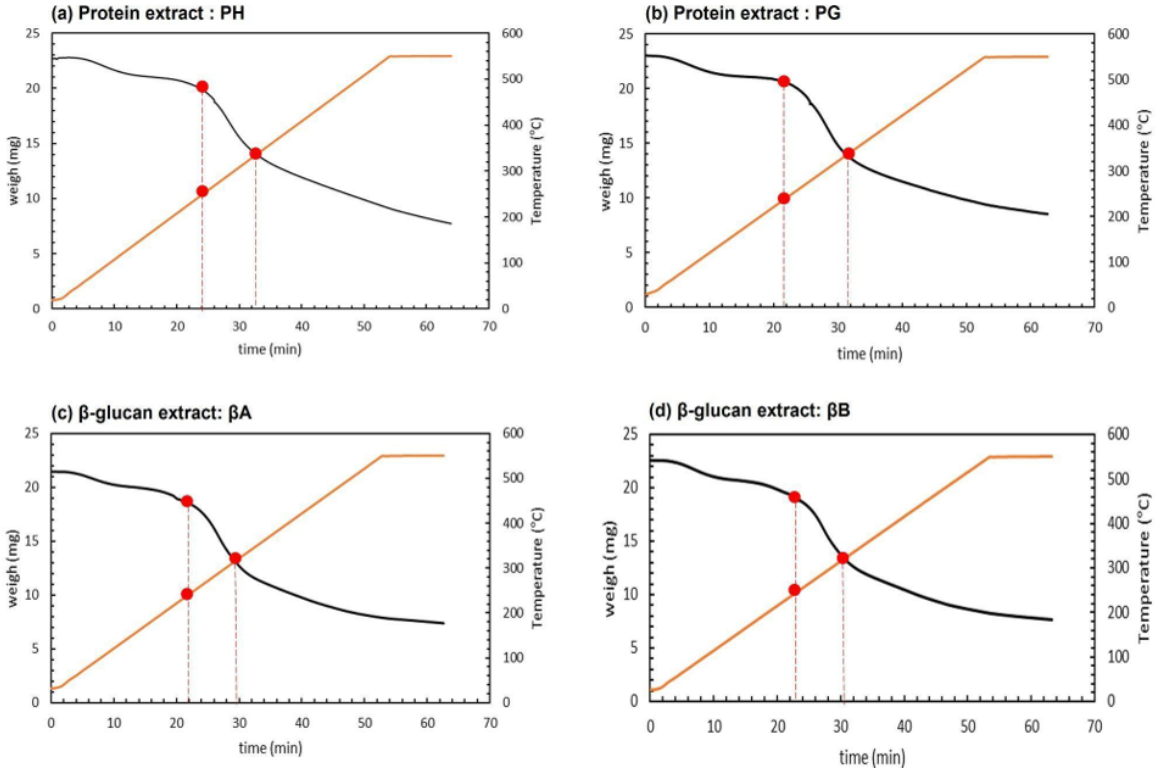

Figure 3: Thermogravimetric analysis (TGA) curves of protein extract (a) and (b), and β-glucan extract (c) and (d). Samples were heated from 30 to 550°C for 60 min (10°C/ per min).

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

[8]Bai, 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 efficiency[9]. 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 ± SD)	**PG (mean ± SD)**	**BA (mean ± SD)**	**BB (mean ± 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

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