Agro-Waste as a Source of Functional Proteins: Extraction, Purification and Applications in Food and Nutraceutical Industries

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ABSTRACT

Agro-waste represents an abundant yet underutilized resource for sustainable protein recovery, offering potential applications in the food and nutraceutical sectors. This review consolidates recent advances in the extraction and purification of proteins from diverse agro-industrial byproducts, including cereal residues, oilseed cakes, fruit peels, and legume husks. Conventional methods such as alkaline and acid extraction remain cost-effective but often compromise protein functionality, while emerging green technologies—enzyme-assisted, ultrasound-assisted, and microwave-assisted techniques—show promise in enhancing yield and preserving bioactive properties. Purification strategies, including membrane filtration, chromatography, and precipitation, are critically compared with respect to scalability, cost, and impact on functional quality.The bioactive potential of agro-waste-derived proteins, particularly peptides with antioxidant, antimicrobial, and antihypertensive properties, underscores their nutraceutical relevance. However, challenges such as variability in raw materials, high operational costs, and lack of clinical validation hinder large-scale adoption. The discussion highlights the trade-off between protein yield and functionality, as well as the need for integrated, multidisciplinary approaches to optimize recovery systems. Within the framework of sustainability and circular economy principles, protein mining from agro-waste offers a dual advantage of value addition and waste minimization. Future research should focus on scaling up green technologies, standardizing quality assessment, and exploring regulatory pathways for commercial application. Overall, agro-waste proteins present a promising avenue toward sustainable food security and nutraceutical innovation.

Keywords: protein extraction, purification, nutraceuticals, sustainability, circular economy

INTRODUCTION AND BACKGROUND

The increased global demand for sustainable protein sources is being driven by population growth, altering dietary choices, and the expanding functional food and nutraceutical markets. Traditional protein sources, such as soy, wheat, and animal-derived proteins, are increasingly attacked for their environmental impact and resource intensity. Consequently, attention has switched to alternate, underutilized protein reserves that fit within circular economy principles. The leftover biomass from the food processing and agricultural sectors is known as agro-waste, and it has shown promise as a remedy. It contributes to environmental degradation since it is produced in enormous amounts worldwide and frequently used in low-value applications like animal feed, composting, or, occasionally, disposal [1, 2].

In addition to addressing waste management issues, valorizing agro-waste through protein recovery promotes the creation of innovative, sustainable protein constituents. The conversion of residues into high-value functional proteins with nutritional and bioactive qualities is made possible by the integration of agro-waste usage into a zero-waste biorefinery framework, which is in line with global sustainability goals [3, 4]. By increasing yield, lowering environmental effect, and maintaining protein functionality, recent developments in extraction and purification technologies further increase the viability of this strategy. The extraction and purification techniques, techno-functional and bioactive characteristics, and possible uses in the food and nutraceutical industries are highlighted in this overview of agro-waste as a source of functional proteins.

Protein-Rich Agro-Waste Streams

Various plant-based residues produced during crop harvesting and industrial processing are referred to as agro-waste. These streams vary greatly in composition, particularly in protein concentration, and so require specific

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valorization procedures. Cereal processing by-products such as rice bran and wheat bran contain between 12–19% protein on a dry weight basis and are high in albumins and globulins. However, their stability is hampered by high lipid content and the presence of phytic acid, which might affect protein bioavailability [5] . Similar to this, brewers' wasted grain (BSG), the most common by-product of the brewing industry, has significant quantities of fiber and lignin along with about 20–30% protein, mostly glutelins and hordeins, making it both a rich source of protein and difficult to handle [6, 7].

Another significant group of residues that are high in protein is oilseed cakes and meals. For instance, sunflower meal has a good amino acid profile and 30–45% protein, but phenolic chemicals such chlorogenic acid impair its functional qualities [8, 9, 10]. Meals made from soybeans, peanuts, and sesame also have high protein contents and balanced amino acid compositions; however, allergenicity and anti-nutritional factors limit their widespread use [8].

On the other hand, the protein content of fruit and vegetable residues, such as pomace, peels, and seeds, is typically lower (5–10%). However, when paired with protein recovery, these streams' abundance of phenolics, fibers, and leftover sugars can produce multifunctional components with both nutritional and functional advantages [1]. The need of creating efficient, source-specific protein extraction and purification techniques is highlighted by the compositional diversity of these agro-waste resources.

protein percentage in agro-waste

agro-waste	protein content (% dry weight)	key protein types	Notes/challenges
Rice bran	12 - 16 %	Albumins, globulins	High lipids & phytic acid reduce stability
Wheat bran	14 - 19 %	Globulins, glutelins	Rich in fiber, lower digestibility
Brewers spent grain	20 - 30 %	Glutelins, hordeins	High lignocellulose, needs pretreatment
Sunflower meal	30 - 45 %	Albumins, globulins	Presence of chlorogenic acid (anti-nutrient)
Soybean meal	40 - 50 %	Balanced essential amino acids	Allergenicity concerns
Peanut meal	45 - 50 %	Globulins (arachin conarachin)	Allergenicity, aflatoxin risk
Sesame cake	35 - 45 %	Albumins, globulins	Bitter phenolics present
Fruit pomace	5 - 10 %	Mixed proteins + polyphenols	Low protein yield, rich in antioxidants
Vegetable residues	5 - 10 %	Mixed proteins	Low protein yield but multifunctional

Table 1: Protein percentage in different agro-wastes

Extraction Strategies

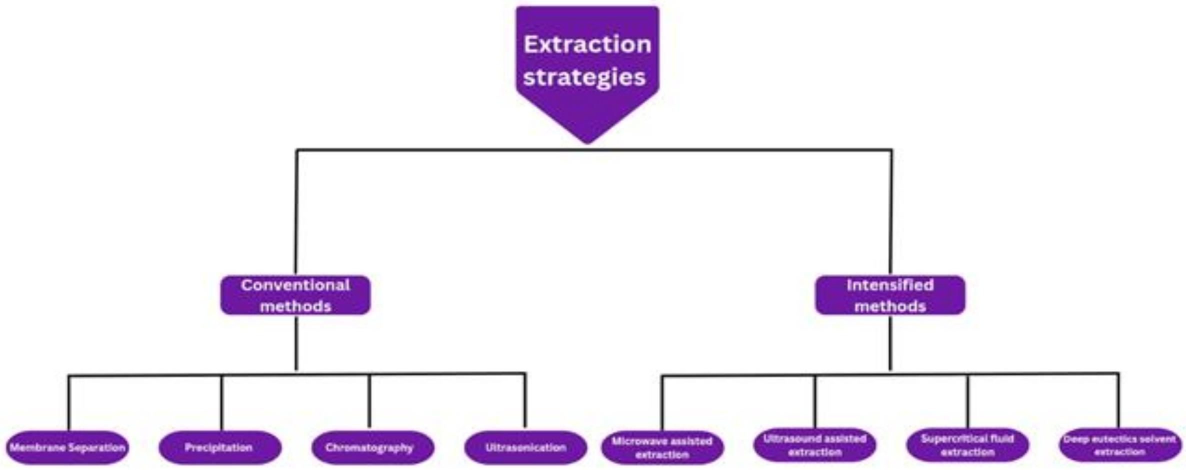

Fig 1: Types of extraction strategies

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The massive amount of waste generated that leads to pollution and other economic losses. In the agriculture waste, these waste streams are bioactive compounds in nature. Proteins have the feasibility to recover and reutilize as foods, cosmetics and medications.

Conventional methods

In the conventional methods, it includes membrane extraction, precipitation, chromatography and ultrasonication.

Membrane Separation:

Membrane filtration techniques, like as ultrafiltration (UF), are commonly applied to remove and concentrate postbiotic compounds from fermentation broths. UF can fractionate metabolites by molecular weight, allowing separation of low-molecular-weight peptides, exopolysaccharides, and tiny organic acids from the bulk media. For instance, a study indicated that membrane ultrafiltration is possible as a single-step clarifying and fractionation approach for microbial protein hydrolysates [11]. Similarly, the scientists recovered the lipopeptide surfactin from Bacillus subtilis fermentation broth using a two-stage membrane technique. They achieved considerable purification utilizing a 10 kDa MWCO regenerated cellulose membrane [12].

Precipitation:

Precipitation is a classical technique to recover proteins or peptides by altering their solubility via pH shifts or addition of salts or solvents. For example, after fermentation, bacteriocins can be precipitated by adjusting pH or using ammonium sulfate, enabling partial purification from the culture supernatant [13]. Though effective and low-cost, precipitation often yields crude mixtures that may require further downstream purification to remove contaminants or achieve high purity.

Chromatography:

Ion-exchange, size-exclusion, and reversed-phase chromatographic methods are highly effective at separating high-purity postbiotic fractions. Ion-exchange chromatography can selectively bind charged peptides or bacteriocins, separating them based on their isoelectric points, while size-exclusion (gel filtration) separates molecules by size. Although less prevalent for large-scale extraction, chromatography remains the gold standard when high purity or bioactivity is required [14].

Ultrasonication:

Applying high-frequency sound waves to the fermentation broth causes cavitation, which breaks down cell walls and improves the mass transfer of intracellular and extracellular metabolites. This process is known as ultrasonication, or sonication. This technique is very helpful for releasing peptides, cell-wall fragments, or cell-associated enzymes. However, severe sonication can destroy sensitive molecules, therefore adjustment of amplitude and duration is critical [15].

Green/Intensified methods:

Green method is the process in which it mainly prioritizes the environmental conditions and it reduces the energy consumption and waste generation. Intensified method is the process that helps to enhance efficiency and productivity that reduces the time and cost of this process. It uses advanced technologies including microwave and ultrasound energy.

Green/Intensified extraction techniques includes techniques are microwave assisted extraction, ultrasound assisted extraction, supercritical fluid extraction and Deep eutectics solvent extraction.

Microwave-assisted extraction:

Microwave-assisted extraction increases cell permeability and releases metabolites by quickly heating the aqueous phase within microbial biomass using non-ionizing microwave radiation. When compared to

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traditional heating, this technique significantly shortens extraction times and uses less solvent. In one microbiological environment (algae), a combination MAE and supercritical CO_2 extraction revealed large amounts of lipophilic bioactive chemicals [16]. Even though this example is for algae, the principle applies equally to microbial systems, especially for thermally stable exopolysaccharides or hydrophobic peptides [17].

Ultrasound Assisted Extraction (UAE):

Although UAE and ultrasonication are comparable, UAE is typically more regulated and tailored for metabolite recovery. It enhances solvent penetration and mass transfer by gently disrupting cell walls with lower frequencies and intensities. Because of its gentle conditions, UAE is useful for recovering fragile peptides, organic acids, and exopolysaccharides without severe degradation.

Supercritical fluid extraction:

Supercritical fluid extraction, notably with CO_2, is a “green” extraction technology that harnesses supercritical CO_2’s customizable solvent properties. SFE can selectively solubilize non-polar or moderately polar postbiotic substances. For instance, carotenoids, fatty acids, and tocopherols were successfully extracted from cyanobacteria using supercritical CO2 and a co-solvent with good bioactivity retention [18]. Although SFE doesn't leave any hazardous solvent residues, it can be limited by the high expense of high-pressure equipment and the low solubility of highly polar chemicals.

Deep eutectics solvent extraction:

Deep eutectic solvents (DES) are developing as versatile, biodegradable, and customisable solvents for green extraction. A study using a natural DES (choline chloride-based) exhibited effective extraction of bioactive isoflavones with enzyme-mediated augmentation [19]. Moreover, a combined DES–microwave-assisted extraction (DES–MAE) technique has been employed for analytical recoveries of trace chemicals, confirming the compatibility of DES with microwave radiation [19]. For postbiotic applications, DES could be tuned to improve solubility for peptides, polysaccharides, or tiny metabolites, while retaining biocompatibility and limiting environmental toxicity.

Purification And Fractionation

Crude protein fractions frequently need to be purified after extraction in order to enhance quality, eliminate anti-nutritional components, and modify functionality for particular food or nutraceutical uses. Membrane-based technologies, including ultrafiltration (UF) and nanofiltration (NF), are frequently adopted due to their scalability, chemical-free operation, and ability to concentrate proteins while eliminating low-molecular-weight contaminants. Membrane fouling and the requirement for pretreatment, however, continue to be major obstacles [20, 21]. Dialysis and ion-exchange chromatography are often utilized in laboratory-scale investigations to yield high-purity protein isolates, especially from rice bran and sunflower meal proteins. Although these techniques offer superior selectivity and enhance functional characteristics like emulsification and solubility, they are prohibitively expensive for large-scale operations. Similar to this, bioactive peptides are extracted from fruit pomace and vegetable residues using size-exclusion and affinity chromatography, increasing their potential as nutraceuticals. Green extraction methods are increasingly being combined with advanced purification strategies. For example, enzyme-assisted extraction coupled with ultrafiltration has been shown to generate high-quality proteins from fruit pomace with maintained antioxidant activity [22]. Similarly, under mild conditions, aqueous two-phase systems (ATPS) have been utilized to selectively partition proteins from oilseed meals; however, their applicability is limited by the cost of polymers and subsequent recovery operations [21]. In summary, while membrane separation remains the most promising scalable technology, integrating it with biorefinery approaches—such as sequential extraction of proteins, polyphenols, and fibers—could boost the overall economic and environmental sustainability of agro-waste usage.

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Purification and functional properties of agro-waste proteins

Agro-waste protein source	Purification method(s)	Functional properties	potential applications	C
Rice bran ptotein	Ultrafiltration, dialysis	Good solubility, foaming, emulsification	Bakery, beverages	
BSG protein	Membrane filtration, chromatography	Moderate solubility, high water binding	Protein supplements, meat analogues	
Sunflower protein isolates	Dialysis, ultrafiltration, chromatography	Good emulsification limited solubility	Emulsifiers, dairy alternatives	
Soy protein concentrate	Precipitation, Membrane concentration	High gelation, foaming	Plant-based meat, protein powders	
Peanut protein	Ultrafiltration, enzymatic hydrolysis	Good emulsification, alergenicty concerns	Bakery, beverages (after hypoallergenization)	
Sesame protein	Chromatography, membrane separation	Antioxidant activity, moderate solubility	Nutraceuticals functional foods	
Fruit pomace protein	Enzyme-assisted + Membrane filtration	Low solubility but bioactive peptides	Functional beverages, dietary supplements	
Vegetable residue protein	Ultrafiltration, Ion exchange chromatography	Variable solubility, antioxidant peptides	Food fortification, nutraceuticals	

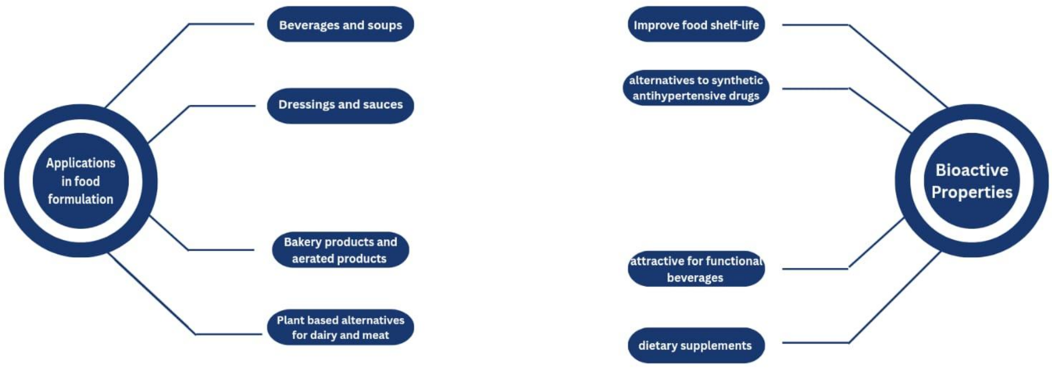
Table 2: Purification strategies for proteins from different agro-wastes and their functional properties and potential applications.

Functional And Bioactive Properties

Agro-waste-derived proteins are increasingly acknowledged not only as nutritional supplements but also as functional food components. Their techno-functional qualities such as solubility, emulsification, foaming, and gelling—are crucial in defining their applicability in food compositions. For instance, proteins extracted from rice bran and sunflower grains demonstrate good solubility at neutral pH, making them acceptable for drinks and soups . Oilseed cake proteins, particularly from soybean and rapeseed, have significant emulsifying potential, enabling their usage in dressings, sauces, and meat analogues [23].

Similarly, because of their surface-active qualities, proteins isolated from fruit pomace—such as grape and apple residues—show improved foaming capacity, which is beneficial for baked goods and aerated sweets. Gelling capability, shown in potato peel and legume husk proteins, is significant for building plant-based alternatives to dairy and meat [22]. Agro-waste proteins are a rich source of bioactive peptides with potential for use in nutraceuticals, in addition to their functional roles in food systems. Hydrolysis of oilseed and cereal bran proteins generates peptides with antioxidant activity, which can alleviate oxidative stress and improve food shelf-life [24]. Several investigations have revealed antihypertensive peptides from rice bran and soybean meal proteins that inhibit angiotensin-converting enzyme (ACE), presenting them as natural alternatives to synthetic antihypertensive medications [25]. Furthermore, fruit pomace and brewer's wasted grain peptides have demonstrated antibacterial and anti-inflammatory properties, which makes them appealing for use in dietary supplements and functional drinks [26]. Importantly, the techno-functional and bioactive qualities are strongly influenced by the extraction and purification procedure utilized. Enzyme-assisted extraction frequently preserves natural protein structure and promotes solubility, while heat techniques may denature proteins, reducing functionality but sometimes enhancing digestibility and bioactivity [27]. For instance, by generating proteins with smaller molecular sizes and more surface activity, ultrasound-assisted extraction enhances emulsifying and foaming ability [28]. Protein isolates with enhanced functional stability and concentrated bioactive fractions are also produced using membrane purification methods [21].

Overall, agro-waste proteins offer a dual advantage, they serve as functional ingredients in food processing while also delivering bioactive compounds that support human health. These multifunctional attributes strengthen the case for their inclusion in both food and nutraceutical formulations, aligning with consumer demand for natural, health-promoting products.



Application

Agro-waste proteins are increasingly being used as functional ingredients in food products, improving their sustainability and quality. One of the most prevalent applications is protein fortification of staple meals and beverages. For instance, to increase protein digestibility and nutritional value, rice bran and soybean meal proteins have been added to noodles and baked goods [23]. Similar to this, breakfast cereals and snack bars are using proteins from fruit pomace and brewer's waste grain (BSG) to increase protein content and add dietary fiber. In plant-based formulations, agro-waste proteins act as texturizers and emulsifiers in meat analogues, dairy alternatives, and dressings, helping simulate the taste properties of animal-derived goods .

Another growing application is the production of functional and probiotic beverages. Proteins produced from fruit and vegetable residues boost the stability of probiotic strains and improve beverage texture. For instance, hydrolyzed proteins from potato peels and bean husks have been included into non-dairy drinks, delivering both nutritional boost and antioxidant activity [22]. Similarly, bioactive peptides generated from oilseed meals are being examined as natural stabilizers in sports and energy drinks, giving not only functionality but also extra health advantages [24].

Agro-waste proteins are becoming more and more important in the nutraceutical industry in addition to food applications. Rice bran, soybean, and sunflower meal protein hydrolysates and bioactive peptides have anti-inflammatory, antihypertensive, and antioxidant qualities that make them appropriate as components of functional capsules and dietary supplements [25]. For example, ACE-inhibitory peptides from rice bran have been converted into nutraceutical formulations targeting blood pressure management [26]. In a similar vein, fruit pomace antimicrobial peptides are being investigated for use as natural preservatives in nutraceutical tablets and powders.

Agro-waste proteins are being used in creative product creation beyond traditional uses. Edible films and coatings generated from oilseed and fruit residues are receiving attention as sustainable packaging materials, boosting food shelf-life by combining barrier qualities with antibacterial and antioxidant activity [21]. Additionally, protein isolates from brewer’s leftover grain are being employed in microencapsulation of bioactives such as probiotics and polyphenols, boosting stability and controlled release in both food and nutraceutical products [28].

Taken together, the diverse applications of agro-waste proteins highlight their potential to bridge food security, sustainability, and human health. By integrating these proteins into mainstream food and nutraceutical industries, it is possible to reduce waste, lower reliance on animal protein, and develop high-value products that meet the rising demand for plant-based and health-oriented solutions.

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Safety, Quality And Regulatory Perspectives

Technical and Feedstock Challenges

The heterogeneity and variability of feedstocks is a significant technical obstacle to large-scale protein recovery from agro-waste. Agro-waste streams varied by crop, season, geographic origin, and processing history, leading to broad changes in protein concentration, composition, and matrix complexity. According to [29], this heterogeneity makes process standardization more difficult and lowers yield and functionality predictability. High lignocellulosic content in residues such as brewers' spent grain and hulls needs energy- or enzyme-intensive pretreatments to free proteins, which increases process complexity and expense [30].

Scale-up, Process Integration and Economic Constraints

Although many green extraction technologies (e.g., ultrasonic, PEF, subcritical water, ATPS) demonstrate promise laboratory-scale performance, scale-up remains hard. Issues include equipment expenses (PEF and subcritical systems), unequal energy distribution (microwave), and complex mass/energy balances when combining unit operations [31, 32, 33]. Although membrane-based concentration and polishing are appealing for industrial use, OPEX and lifespan performance are greatly impacted by fouling, cleaning needs, and membrane replacement expenses [34]. Techno-economic assessments show that profitability often hinges on co-product valorization (fibers, polyphenols, lipids) within a biorefinery concept: isolating proteins alone rarely captures sufficient value to offset CAPEX unless integrated with higher-value side streams [35, 36].

Safety, Quality Control, and Regulatory Hurdles

Commercialization potential is limited by safety issues. Agro-waste may contain anti-nutritional factors (phytates, tannins, chlorogenic acid), mycotoxins (especially in oilseed and grain residues), pesticide residues, and heavy metals depending on crop and handling; all must be monitored and mitigated during extraction and purification [37, 38]. Another crucial concern is allergenicity; before being used in food or nutraceuticals, proteins from peanut, soybean, and certain seed meals must undergo proven procedures for hypoallergenization and regulatory substantiation [39]. Jurisdiction-specific regulatory systems differ; proving GRAS status (or similar), safety/toxicology evidence, and consistent quality is expensive and time-consuming, resulting in non-technical hurdles to market access. [40].

Consumer Acceptance and Sensory Constraints

Beyond safety and costs, customer perception and sensory acceptability are key restraints. Products created from "waste" have psychological hurdles; communication tactics emphasizing sustainability, circularity, and demonstrated quality are vital. To satisfy consumer expectations, optimal fractionation, deodorization, and formulation techniques must be used to resolve sensory problems such as off-flavors, color, or texture alterations brought about by residual lipids, phenolics, or Maillard products.[41, 42].

Environmental and Life-Cycle Considerations

While valorization decreases waste, several extraction methods have non-trivial environmental footprints (energy use, water use, solvent disposal). Life-cycle assessment (LCA) comparisons reveal that green, low-solvent processes integrated within biorefineries often outperform single-product chains, although real-world LCAs are highly sensitive to local energy mixtures and process limitations. As a result, proper environmental accounting must go hand in hand with scalability. [35, 43]

Future Prospects and Research Opportunities

Despite these limitations, some evident opportunities can drive adoption:

To increase economics and resource efficiency, integrated biorefinery models co-produce oils, fibers, proteins, and polyphenols. Hybrid processing flowsheets combining moderate enzymatic pretreatment with intensification techniques (UAE, PEF) and membrane polishing to increase yield while keeping functionality.

[44, 45] To reduce OPEX and allow continuous operation, advanced membrane materials and anti-fouling techniques are used [46]. Digital tools (DoE, machine learning, digital twins) help optimize multi-parameter processes across diverse feedstocks and scale-up approaches, minimizing experimental burden and expediting commercialization. Standardized safety and analytical frameworks (heavy metal screening, peptide fingerprinting, allergy testing, and mycotoxin panels) help expedite regulatory filings and foster customer confidence

In summary, the path from promising lab-scale methods to reliable, profitable industrial lines requires multidisciplinary innovation: process engineering, materials science, regulatory science, LCA, and consumer research [40]. Addressing feedstock variability, improving process economics through co-product valorization, ensuring safety and regulatory compliance, and crafting compelling consumer narratives are all necessary steps to realize the potential of agro-waste-derived proteins in sustainable food and nutraceutical systems.

Techno-Economics And Sustainability

Valorization of agro-waste proteins is firmly connected with the ideas of a circular bioeconomy, where residues are reintroduced into the value chain instead of being discarded. Millions of tons of oilseed cakes, fruit pomace, cereal bran, and vegetable residues are produced annually by food processing worldwide; the majority of these materials are either underutilized or simply employed as low-value animal feed. Protein recovery from these resources provides not only a sustainable alternative to animal protein but also minimizes environmental burdens associated with waste disposal, such as greenhouse gas emissions and water pollution [36]. Protein extraction is increasingly considered as a way to maximize ecological and economic efficiency in biorefinery systems. In such approaches, proteins are co-extracted alongside high-value polyphenols, fibers, and oils, assuring near-zero waste formation [47]. Life-cycle assessments (LCAs) indicate that combining green extraction technologies—such as enzyme-assisted extraction, ultrasound, and membrane separations—with renewable energy inputs can significantly reduce carbon and water footprints compared to conventional protein production systems [48]. From a societal viewpoint, agro-waste valorization promotes food security by broadening the portfolio of accessible protein sources and lowering reliance on conventional animal production, which is resource-intensive and associated to high GHG emissions. [39]. Additionally, by establishing new value chains for crop wastes and food processing by-products, it offers chances for small-scale businesses and rural communities. Taken together, agro-waste protein recovery represents a tangible route toward accomplishing UN Sustainable Development Goals (SDGs) linked to zero hunger, responsible consumption and production, and climate action.

DISCUSSION

The review of current literature indicates that while multiple extraction and purification strategies have been explored for recovering proteins from agro-waste, there is still no single universally applicable method. Conventional methods such as alkaline extraction are cost-effective but often compromise protein quality [49]. In contrast, novel green technologies like ultrasound-assisted or enzyme-assisted extraction preserve functional and bioactive properties but face challenges in scalability and economic feasibility. Another major point of discussion is the trade-off between functionality and yield. For example, membrane-based purification methods yield high-purity proteins suitable for food applications but are limited by fouling and operational costs. Conversely, low-cost precipitation approaches provide higher recovery but result in poor solubility and reduced bioactivity. This highlights the importance of process integration, where combined methods may achieve a balance between efficiency and quality.The bioactive potential of agro-waste proteins has been widely documented, especially peptides with antioxidant and antihypertensive activities [50]. However, most findings are limited to in vitro studies. There is a lack of robust in vivo and clinical validation, which restricts the translation of these proteins into approved nutraceutical formulations. Additionally, variations in raw material composition due to agricultural practices and seasonal differences pose a barrier to reproducibility and regulatory approval. Overall, the discussion points to the need for multidisciplinary approaches—combining food chemistry, bioprocess engineering, and regulatory science—to overcome current bottlenecks. Aligning these efforts with sustainability frameworks can position agro-waste proteins as viable mainstream food and nutraceutical ingredients.

CONCLUSION

Agro-waste represents an abundant, underutilized reservoir of proteins with significant potential for food and nutraceutical applications. Over the last decade, advances in extraction and purification methods—ranging from conventional alkaline precipitation to innovative techniques such as ultrasound, pulsed electric fields, and enzyme-assisted extraction—have greatly improved yields and preserved bioactive functionality. Purification strategies such as membrane separations and aqueous two-phase systems have further enabled production of high-quality protein isolates and peptides tailored for industrial needs Beyond their functional roles in food formulations, agro-waste proteins deliver bioactive peptides with antioxidant, antihypertensive, anti-inflammatory, and antimicrobial activities, strengthening their nutraceutical value. However, several challenges remain—notably feedstock variability, scale-up costs, safety and regulatory hurdles, and consumer perception issues. Addressing these requires multidisciplinary approaches integrating bioprocess engineering, regulatory science, life-cycle assessment, and consumer-focused innovation. Looking forward, the future of agro-waste protein utilization lies in biorefinery-based models, where proteins are valorized alongside other high-value co-products to achieve economic feasibility and environmental sustainability. If these innovations are combined with effective safety assurance and consumer engagement strategies, agro-waste proteins could transition from niche applications to mainstream functional ingredients and supplements. Ultimately, transforming “waste into wealth” offers a pathway toward a sustainable, resilient, and health-oriented food system.

REFERENCES

1. Motasem Y.D. Alazaiza, Aiman A. Bin Mokaizh, Abdullah O. Baarimah, Tharaa Al-Zghoul, From agro-waste to bioactive wealth: Analyzing nutraceutical extraction and applications, Case Studies in Chemical and Environmental Engineering, 11, 2025, 101066, ISSN 2666-0164, https://doi.org/10.1016/j.cscee.2024.101066
2. Nadar, C. G., Fletcher, A., Moreira, B. R. A., Hine, D., & Yadav, S. (2024). Waste to protein: A systematic review of a century of advancement in microbial fermentation of agro-industrial byproducts. Comprehensive Reviews in Food Science and Food Safety, 23, e13375. https://doi.org/10.1111/1541-4337.13375
3. Arun Kumar Pandey, Sheetal Thakur, Rahul Mehra, Raj Sukhwinder Singh Kaler, Maman Paul, Arun Kumar, Transforming Agri-food waste: Innovative pathways toward a zero-waste circular economy, Food Chemistry: X, 28, 2025, 102604, ISSN 2590-1575, https://doi.org/10.1016/j.fochx.2025.102604
4. Turning Food Protein Waste into Sustainable Technologies Mohammad Peydayesh, Massimo Bagnani, Wei Long Soon, and Raffaele Mezzenga Chemical Reviews 2023 123 (5), 2112-2154 DOI: 10.1021/acs.chemrev.2c00236
5. Research Progress on the Quality, Extraction Technology, Food Application, and Physiological Function of Rice Bran Oil By Wengong Huang, Baohai Liu ,Dongmei Shi ,Aihua Cheng ,Guofeng Chen ,Feng Liu ,Jiannan Dong ,Jing Lan ,Bin Hong ,Shan Zhang 3ORCID andChuanying Ren Foods 2024, 13(20), 3262; https://doi.org/10.3390/foods13203262
6. Aradwad, P., Raut, S., Abdelfattah, A., Rauh, C., & Sturm, B. (2025). Brewer’s spent grain: unveiling innovative applications in the food and packaging industry. Comprehensive Reviews in Food Science and Food Safety, 24, e70150. https://doi.org/10.1111/1541-4337.70150
7. Extraction, Composition, Functionality, and Utilization of Brewer’s Spent Grain Protein in Food Formulations By Bhanu Devnani,Galo Chuchuca MoranORCID andLutz Grossmann *Foods 2023, 12(7), 1543; https://doi.org/10.3390/foods12071543
8. Milad Hadidi, Fatemeh Aghababaei, David Julian McClements, Sunflower meal/cake as a sustainable protein source for global food demand: Towards a zero-hunger world, Food Hydrocolloids, 147, Part A, 2024, 109329, ISSN 0268-005X, https://doi.org/10.1016/j.foodhyd.2023.109329
9. RamanPreet Kaur, Gargi Ghoshal, Sunflower protein isolates-composition, extraction and functional properties, Advances in Colloid and Interface Science, 306, 2022, 102725, ISSN 0001-8686
10. Sunflower seed byproduct and its fractions for food application: An attempt to improve the sustainability of the oil process Josemar Gonçalves de Oliveira Filho, Mariana Buranelo Egea First published: 21 April 2021 https://doi.org/10.1111/1750-3841.15719

11. Yadav, M. K., Song, J. H., Vasquez, R., et al. Methods for Detection, Extraction, Purification, and Characterization of Exopolysaccharides of Lactic Acid Bacteria. Foods, 2024. DOI: https://doi.org/10.3390/foods13223687
12. Mohd Hafez Mohd Isa, Richard A. Frazier, Paula Jauregi, A further study of the recovery and purification of surfactin from fermentation broth by membrane filtration, Separation and Purification Technology, 64, 2, 2008, Pages 176-182, ISSN 1383-5866, https://doi.org/10.1016/j.seppur.2008.09.008
13. Vadekeetil, A. Purification of bacteriocin using ammonium sulfate precipitation. International Research Journal of Biological Sciences, 2015. Link: https://www.isca.in/IJBS/Archive/v4/i8/4.ISCA-IRJBS-2015-096.pdf
14. Yap, P.G., Lai, Z.W. & Tan, J.S. Bacteriocins from lactic acid bacteria: purification strategies and applications in food and medical industries: a review. Beni-Suef Univ J Basic Appl Sci 11, 51 (2022). https://doi.org/10.1186/s43088-022-00227-x
15. Farid Chemat, Zill-e-Huma, Muhammed Kamran Khan, Applications of ultrasound in food technology: Processing, preservation and extraction, Ultrasonics Sonochemistry, 18, 4, 2011, Pages 813-835, ISSN 1350-4177, https://doi.org/10.1016/j.ultsonch.2010.11.023
16. Esquivel-Hernández, D. A., López, V. H., Rodríguez-Rodríguez, J., Alemán-Nava, G. S., Cuéllar-Bermúdez, S. P., Rostro-Alanis, M., & Parra-Saldívar, R. (2016). Supercritical Carbon Dioxide and Microwave-Assisted Extraction of Functional Lipophilic Compounds from Arthrospira platensis. International Journal of Molecular Sciences, 17(5), 658. https://doi.org/10.3390/ijms17050658
17. Athira Jayasree Subhash, Gafar Babatunde Bamigbade, Basel al-Ramadi, Afaf Kamal-Eldin, Ren-You Gan, Chaminda Senaka Ranadheera, Mutamed Ayyash, Characterizing date seed polysaccharides: A comprehensive study on extraction, biological activities, prebiotic potential, gut microbiota modulation, and rheology using microwave-assisted deep eutectic solvent, Food Chemistry, 444, 2024, 138618, ISSN 0308-8146, https://doi.org/10.1016/j.foodchem.2024.138618
18. Tabernero A, Cardea S. Supercritical carbon dioxide techniques for processing microbial exopolysaccharides used in biomedical applications. Mater Sci Eng C Mater Biol Appl. 2020 Jul;112:110940. Doi: 10.1016/j.msec.2020.110940. Epub 2020 Apr 8. PMID: 32409086.
19. Yuntao Dai, Jaap van Spronsen, Geert-Jan Witkamp, Robert Verpoorte, Young Hae Choi, Natural deep eutectic solvents as new potential media for green technology, Analytica Chimica Acta, 766, 2013, Pages 61-68, ISSN 0003-2670, https://doi.org/10.1016/j.aca.2012.12.019
20. Juanjuan Wen, Qing Han, Minghui Qiu, Ling Jiang, Xianfu Chen, Yiqun Fan Membrane technologies for the separation and purification of functional oligosaccharides: A review, Separation and Purification Technology, 346, 2024, 127463, ISSN 1383-5866, https://doi.org/10.1016/j.seppur.2024.127463.
21. atifah Suha Azmi, Nurul 'Ain Jabit, Suhaina Ismail, Ku Esyra Hani Ku Ishak, Tuti Katrina Abdullah, Membrane filtration technologies for sustainable industrial wastewater treatment: a review of heavy metal removal., Desalination and Water Treatment, 323, 2025, 101321, ISSN 1944-3986, https://doi.org/10.1016/j.dwt.2025.101321
22. Li, Yue & Zhang, Xiong & Liu, Xinran & Wu, Yuanhao & Guo, Shuntang. (2023). Effect of protein concentration on thermal aggregation and Ca2+-induced gelation of soymilk protein. Food Hydrocolloids. 145. 109014. 10.1016/j.foodhyd.2023.109014.
23. Klaudia Kotecka-Majchrzak, Agata Sumara, Emilia Fornal, Magdalena Montowska, Oilseed proteins â€" Properties and application as a food ingredient, Trends in Food Science & Technology, 106, 2020, Pages 160-170, ISSN 0924-2244, https://doi.org/10.1016/j.tifs.2020.10.004
24. Olivares-Galván S, Marina ML, García MC. Extraction and Characterization of Antioxidant Peptides from Fruit Residues. Foods. 2020 Jul 29;9(8):1018. doi: 10.3390/foods9081018. PMID: 32751284; PMCID: PMC7466205.
25. Benjamin Bonsu Bruce, Isaac Duah Boateng, Charllote Boateng, Recent advances in bioactive peptides from fermented plant-based foods and their bioactivities, Food Chemistry: X, 32, 2025, 103291, ISSN 2590-1575, https://doi.org/10.1016/j.fochx.2025.103291
26. Machado M, Bautista-Hérnandez I, Gómez-García R, Silva S, Costa EM. Bioactive Food Proteins: Bridging Nutritional and Functional Benefits with Sustainable Protein Sources. Foods. 2025 Aug 29;14(17):3035. doi: 10.3390/foods14173035. PMID: 40941156; PMCID: PMC12428393.

27. Antonio Rocha Bisconsin-Junior, Giacomo Rossi, Sorel Tchewonpi Sagu, Harshadrai M. Rawel, Lilian Regina B. Mariutti, Oliver K. SchlÃ¼ter, Non-thermal technologies modify protein structure and enhance functional properties of cricket protein concentrate, Innovative Food Science & Emerging Technologies, 100, 2025, 103945, ISSN 1466-8564, https://doi.org/10.1016/j.ifset.2025.103945
28. Ben Van den Wouwer, Kristof Brijs, Arno G.B. Wouters, Katleen Raes, The effect of ultrasound on the extraction and foaming properties of proteins from potato trimmings, Food Chemistry, 455, 2024, 139877, ISSN 0308-8146, https://doi.org/10.1016/j.foodchem.2024.139877
29. Joncer Naibaho, MaÅ‚gorzata Korzeniowska, The variability of physico-chemical properties of brewery spent grain from 8 different breweries, Heliyon, 7, 3, 2021, e06583, ISSN 2405-8440, https://doi.org/10.1016/j.heliyon.2021.e06583
30. Claire D Munialo, Derek Stewart, Lydia Campbell, Stephen R Euston, Extraction, characterisation and functional applications of sustainable alternative protein sources for future foods: A review, Future Foods, 6, 2022, 100152, ISSN 2666-8335, https://doi.org/10.1016/j.fufo.2022.100152
31. L. VernÃ¨s, M. Abert-Vian, M. El MaÃ¢taoui, Y. Tao, I. Bornard, F. Chemat, Application of ultrasound for green extraction of proteins from spirulina. Mechanism, optimization, modeling, and industrial prospects, Ultrasonics Sonochemistry, 54, 2019, Pages 48-60, ISSN 1350-4177, hL. VernÃ¨s, M. Abert-Vian, M. El MaÃ¢taoui, Y. Tao, I. Bornard, F. Chemat, Application of ultrasound for green extraction of proteins from spirulina. Mechanism, optimization, modeling, and industrial prospects, Ultrasonics Sonochemistry, 54, 2019, Pages 48-60, ISSN 1350-4177, https://doi.org/10.1016/j.ultsonch.2019.02.016ttps://doi.org/10.1016/j.ultsonch.2019.02.016
32. Fan S, Yin Y, Liu Q, Yang X, Pan D, Wu Z, Du M, Tu M. Blue food proteins: Novel extraction technologies, properties, bioactivities and applications in foods. Curr Res Food Sci. 2024 Oct 9;9:100878. doi: 10.1016/j.crfs.2024.100878. PMID: 39498458; PMCID: PMC11533013.
33. Eman Shawky, Wei Zhu, Jingkui Tian, A review of innovative extraction technologies for protein recovery from plant-based by-products: A step toward zero-waste processing, International Journal of Biological Macromolecules, 315, Part 1, 2025, 144301, ISSN 0141-8130, https://doi.org/10.1016/j.ijbiomac.2025.144301
34. P.R. Yaashikaa, P. Senthil Kumar, Sunita Varjani, Valorization of agro-industrial wastes for biorefinery process and circular bioeconomy: A critical review, Bioresource Technology, 343, 2022, 126126, ISSN 0960-8524, https://doi.org/10.1016/j.biortech.2021.126126
35. Aristotle T. Ubando, Charles B. Felix, Wei-Hsin Chen, Biorefineries in circular bioeconomy: A comprehensive review, Bioresource Technology, 299, 2020, 122585, ISSN 0960-8524, https://doi.org/10.1016/j.biortech.2019.122585.
36. C. Andreola, J. GonzÃ¡lez-Camejo, F. Tambone, A.L. Eusebi, F. Adani, F. Fatone, Techno-economic assessment of biorefinery scenarios based on mollusc and fish residuals, Waste Management, 166, 2023, Pages 294-304, ISSN 0956-053X, https://doi.org/10.1016/j.wasman.2023.05.014
37. Jithender, Bhukya & Upendar, Konga & C., Nickhil & Rathod, P J. (2019). Nutritional and anti-nutritional factors present in oil seeds: An overview. 7. 1159-1165.
38. Kumar, Manoj & Chand, Ramesh & Shah, Kavita. (2018). Mycotoxins and Pesticides: Toxicity and Applications in Food and Feed. 10.1007/978-981-10-7140-9_11.
39. Advances in Food Processing Techniques for Allergenicity Reduction and Allergen Identification by Marta Wójcik 1,Krystian Marszałek 1,*ORCID andEdyta Juszczuk-Kubiak 2,*Foods 2025, 14(22), 3933; https://doi.org/10.3390/foods14223933
40. Hadi J, Brightwell G. Safety of Alternative Proteins: Technological, Environmental and Regulatory Aspects of Cultured Meat, Plant-Based Meat, Insect Protein and Single-Cell Protein. Foods. 2021 May 28;10(6):1226. doi: 10.3390/foods10061226. PMID: 34071292; PMCID: PMC8230205.
41. The Health-Promoting Potential of Fruit Pomace and Its Application in the Confectionery Industry by Anna TamaORCID andMonika Karaś *Appl. Sci. 2025, 15(10), 5790; https://doi.org/10.3390/app15105790
42. Bharti Sharma, Russell Keast, Djin Gie Liem, Yada Nolvachai, Shirani Gamlath, Penelope Oliver, Andrew Costanzo, Plant-protein isolates and flavour perception: Understanding mechanisms and strategies to balance flavour retention and release, Food Chemistry, 493, Part 2, 2025, 145815, ISSN 0308-8146, https://doi.org/10.1016/j.foodchem.2025.145815

43. Esra Imamoglu, Green extraction processes from renewable biomass to sustainable bioproducts, Bioresource Technology Reports, 27, 2024, 101952, ISSN 2589-014X, https://doi.org/10.1016/j.biteb.2024.101952
44. Animesh Sarkar, Md Fuad Al Hasan, Md. Sumon Miah, Abir Mahmud, Mahabub Alam, Comparative assessment of ultrasound and enzyme assisted extraction of rice bran protein following sequential pretreatments: yield, functional properties improvement, and potential application, Applied Food Research, 5, 2, 2025, 101468, ISSN 2772-5022, https://doi.org/10.1016/j.afres.2025.101468
45. Yusree FIFM, Peter AP, Mohd Nor MZ, Show PL, Mokhtar MN. Latest Advances in Protein-Recovery Technologies from Agricultural Waste. Foods. 2021 Nov 9;10(11):2748. doi: 10.3390/foods10112748. PMID: 34829028; PMCID: PMC8618363.
46. Shaofu Du, Peng Zhao, Lingfeng Wang, Gaohong He, Xiaobin Jiang, Progresses of advanced anti-fouling membrane and membrane processes for high salinity wastewater treatment, Results in Engineering, 17, 2023, 100995, ISSN 2590-1230, https://doi.org/10.1016/j.rineng.2023.100995
47. Arunima Saxena, Bijay P. Tripathi, Mahendra Kumar, Vinod K. Shahi, Membrane-based techniques for the separation and purification of proteins: An overview, Advances in Colloid and Interface Science, 145, Issues 1â€“2, 2009, Pages 1-22, ISSN 0001-8686, https://doi.org/10.1016/j.cis.2008.07.004
48. Circular Bioeconomy in Action: Transforming Food Wastes into Renewable Food Resources by Priti Pal 1ORCID,Akhilesh Kumar Singh 2ORCID,Rajesh Kumar Srivastava 3ORCID,Saurabh Singh Rathore 2,Uttam Kumar Sahoo 4ORCID,Sanjukta Subudhi 5ORCID,Prakash Kumar Sarangi 6,*ORCID andPiotr Prus 7,*Foods 2024, 13(18), 3007;
49. Jiayue Tang, Dan Yao, Shuaibo Xia, Lingzhi Cheong, Maolin Tu, Recent progress in plant-based proteins: From extraction and modification methods to applications in the food industry, Food Chemistry: X, 23, 2024, 101540, ISSN 2590-1575, https://doi.org/10.1016/j.fochx.2024.101540
50. Shima Jafarzadeh, Zeinab Qazanfarzadeh, Mahsa Majzoobi, Samira Sheiband, Nazila Oladzadabbasabad, Yasaman Esmaeili, Colin J. Barrow, Wendy Timms, Alternative proteins; A path to sustainable diets and environment, Current Research in Food Science, 9, 2024, 100882, ISSN 2665-9271, https://doi.org/10.1016/j.crfs.2024.100882