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From Agricultural Waste to Valuable Protein: Emerging Technologies for Sustainable Recovery

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Agricultural and food processing industries generate a large variety of by- products, including oilseed meals, cereal bran, fruit pomace and legume residues these materials are often considered waste or low value products. However, they contain significant amounts of protein and other nutrients. Recent studies have demonstrated that agricultural by products are attractive sources of plant proteins for the production of value- added food ingredients. particularly, rice bran, oilseed cakes and legume-processing are of interest for protein recovery. Therefore, appropriate technologies are needed to recover proteins while maintaining their functional and nutritional properties. Protein recovery can reduce waste and increase the value of processing residues by transforming them into valuable ingredients.

Keywords: Agricultural by products; circular economy; plant protein; protein recovery; sustainable processing

Agricultural and food processing activities produce substantial by products and residues that need to be disposed of or utilized for beneficial purposes. However, many by-products contain significant amounts of protein and other biologically active compounds, which can be recovered to produce useful products. Thus, protein recovery from agricultural by products can be an excellent opportunity to reduce waste, recover valuable materials, and create new products. However, the efficient recovery of protein is challenging because proteins are often bound to cell-wall components and other plant polymers. conventional extraction techniques are often laborious, consume large amounts of chemical reagents and water, and may affect the functional properties of proteins. Modern alternative techniques such as ultrasound, enzyme, and microwave assisted extractions as well as high pressure processing, can improve the efficiency and sustainable recovery of protein from plant residues. This article discusses emerging technologies and approaches to recovery efficiency, protein quality and functionality, process, economics, sustainability, and scale- up possibilities.

Agricultural Residues as Protein Resources

Agricultural and food-processing residues differ considerably in their composition and protein content. Materials such as cereal bran, oilseed meals, legume residues, fruit pomace and vegetable-processing residues may contain considerable amounts of protein and therefore have potential for protein recovery utilizing these residues can help convert low-value materials into useful food ingredients while improving the utilization of agriculture resources Karabulut et al., (2023) reported that pea pods contained approximately 10-13% protein. Among the treatments investigated, ultrasound pretreatment followed by alkaline extraction resulted in a protein extract yield of 21.1% under optimized conditions (Karabulut et al.,2023).

Figure 1. Agricultural Residues as protein Resources

Rice bran is another important agro-industrial by-product with considerable potential for protein recovery. Senna et at.,(2025) investigated protein recovery from defatted rice bran using enzymatic pretreatment and ultrasound -assisted extraction. Ultrasound-probe extraction increased protein recovery from 5.4 to 21% whereas the combined use of enzymatic pretreatment and ultrasound resulted in the highest recovery of 43.7% (Senna et al.,2025) These findings demonstrate that the selection and sequence of pretreatment and extraction methods can strongly influence protein recovery from agricultural residues. Protein present in agricultural residues may not be easily extractable because it can interact with cell-wall components and other plant constituents. Therefore appropriate pretreatment and extraction conditions are required to improve protein recovery while maintaining its nutritional quality and functional properties (Shawky et al.,2025) Recent research has consequently explored emerging approaches, including ultrasound -enzyme, microwave-, pressure-and electric-field-assisted extraction, for improving proteins recovery from plant -based residues (Shawky et al.,2025)

Conventional and Emerging Protein Recovery Technologies

Conventional Protein Extraction: Conventional protein extraction methods generally involve the solubilization of proteins from plant materials followed by their separation and recovery. Alkaline extraction is one of the commonly used techniques for recovering proteins from plant materials. The process uses an alkaline medium to increase protein solubility, followed by protein recovery through adjustment of the pH to the isoelectric point of the target proteins (Kamal et.al.,2021). These methods are relatively simple and have been employed for protein extraction from different types of food material and their by -products. However, conventional methods may require large volumes of water and chemical reagents and may involve multiple processing steps. Moreover, the use of harsh extraction conditions may affect the physicochemical, nutritional and functional properties of the extracted proteins (Kamal et al.,2021). Due to these limitations, assisted extraction technologies have been introduced to improve the efficiency of protein recovery. These conditions while reducing processing time and improving protein recovery (Shawky et al.,2025)

Ultrasound-Assisted Extraction (UAE): Ultrasound assisted extraction (UAE) is an one of the technique that has been developed recently to facilitate the release of proteins from plant materials with the aid of high-frequency sound waves that generate cavitation, which leads to disruption of plant tissues and enhanced transfer of proteins into the extraction medium, thus accelerating the mass transfer process and improving the overall extraction efficiency by reducing the time required for protein extraction. (Shawky et.al.,2025). Karabulut et.al.,(2023) investigated the effectiveness of ultrasound pretreatment to recover protein from pea pods containing about 10 to 13%. Ultrasound pretreatment followed by alkaline extraction yielded a protein extract of 21.1% under optimized conditions. (Karabulut et al.,2023). However, the intensity of ultrasound, the duration of the treatment and the temperature need to be optimized to obtain high recovery without compromising protein quality. (Shawky et al.,2025)

Enzyme-Assisted Extraction (EAE): Enzyme-assisted extraction is a process, which involves the application of particular enzymes, capable of degrading the plant tissue cell-wall polysaccharides. This can improve the release of protein and enhance protein recovery compared with conventional extraction method (Shawky et al.,2025). According to Shawky et.al.,(2025) using of an enzymatic reaction allows for obtaining the a better quality of protein under relatively gentle conditions. on the other hand Senna et al.,(2025) state that the combination of an enzymatic pretreatment and ultrasound -assisted extraction resulted in a 43.7% protein recovery from rice bran, compared to only 21% when using ultrasound .However enzyme cost and process optimization can be important considerations for large-scale application.

Other Emerging Technologies

Microwave-assisted extraction uses microwave energy to rapidly heat the extraction medium. This can improve the release and recovery of proteins from plant materials. High-pressure processing can cause structural changes in the plant matrix, which may improve protein recovery yield. Another technique is pulsed electric field, which can increase the permeability of plant cells and make protein release easier. Natural deep eutectic solvents can replace some conventional chemical solvents and support more sustainable protein extraction. Membrane filtration can be used to concentrate and purify the recovered proteins.

Table 1- Comparison of protein recovery technologies

Protein recovery technology	Main principle	Advantage	Limitation
Conventional extraction	Protein solubilization followed by separation	Simple and well-established	High water and chemical consumption
Ultrasound-Assisted Extraction (UAE)	Cavitation disrupts plant tissues and enhances protein release	Faster extraction	Requires optimization of intensity, time and temperature
Enzyme-Assisted Extraction (EAE)	Enzymes break down plant cell-wall components	Better protein release under mild conditions	Enzyme cost
Microwave-Assisted Extraction (MAE)	Microwave energy rapidly heats the extraction medium	Rapid heating and extraction	Temperature control required
High-Pressure Processing (HPP)	High pressure changes the plant matrix	Can improve protein recovery	High equipment cost
Pulsed Electric Field (PEF)	Increases cell permeability	Facilitates protein release	Scale-up challenges
Natural Deep Eutectic Solvents (NADES)	Alternative solvent systems are used for extraction	More sustainable extraction	Solvent selection and optimization required
Membrane filtration	Membrane-based separation and concentration	Useful for protein purification and concentration	Membrane fouling and operating conditions

Source: Compiled from Kamal et al. (2021) and Shawky et al. (2025).

Hybrid Extraction Technologies

Hybrid extraction is one of the methods used for protein recovery from agriculture by-products. It involves combining two or more extraction methods. For example, the combination enzymatic pretreatment and ultrasound treatment can improve protein recovery. According to Senna et al. (2025), enzymatic pretreatment of defatted rice bran followed by ultrasound treatment increased protein recovery compared with ultrasound treatment alone. Combining two or more methods can improve protein recovery and reduce some limitations associated with individual extraction methods. However, suitable operating conditions and cost effectiveness need to be considered for industrial applications.

Sustainability, Economics and Scale-Up

Protein recovery from agricultural by-products can create value from waste materials and improve the utilization of available resources. Converting these low-value materials into protein-rich ingredients can provide economic benefits to food-processing industries. Moreover, sustainable extraction technologies can reduce the consumption of water, chemicals and energy. However, the application of these technologies at a large or industrial scale requires appropriate equipment, continuous processing system and cost-effective operating conditions. Therefore, process optimization, energy consumption, raw-material availability and product quality should be considered for successful industrial scale-up.

Future Prospects

Protein recovery from agricultural by-products has significant potential for developing sustainable and value-added ingredients. In the future, research should focus on increasing protein recovery yield while maintaining the nutritional and functional properties of the recovered proteins. The development of low-cost and energy-efficient technologies will facilitate their application at the industrial level. Further research is needed to improve the quality, safety, and stability of protein products. Combining different extraction techniques and using suitable green processing approaches may help in the development of a circular food-processing system.

Summary

By-products from agriculture and food-processing industry are rich in protein and these can be effectively recovered and applied as value-added food components. Novel technologies like ultrasonic extraction, enzyme-assisted extraction, microwave-assisted extraction, high pressure processing, and pulsed electric field can increase the recovery rate of proteins when compared to traditional processes. A combination of two or more techniques can increase the efficiency of extraction with good protein quality and functionality. There should be development of cost-effective, energy-saving and sustainable technologies that can be effectively used in industries. Effective use of by-products can promote waste management and resource optimization.

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