Enzyme-Assisted Valorization of Plant Bioresources for Functional Bioproducts. A review

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Plant bioresources are an abundant, sustainable, and underutilized source of essential bioactive substances for use in the food, pharmaceutical, cosmetic, and nutraceutical sectors. The increased demand for sustainable and environmentally friendly processing technologies has fueled interest in enzyme-assisted valorization as a greener alternative to traditional extraction methods. This review emphasizes the relevance of plant bioresources and functioning bioproducts, particularly the use of enzymes in green extraction methods. The many kinds of hydrolytic and oxidative enzymes that contribute to biomass valorization are described, as well as their modes of action. Uses of enzyme-assisted extraction in the production of functional bioproducts are discussed, followed by a review of commercial scale-up issues, economic feasibility, and regulatory implications. In terms of sustainability, selectivity, and environmental effect, enzyme-assisted approaches can outperform traditional, microwave, ultrasound, and pressurized liquid extraction procedures. Enzymes can selectively break down complex polysaccharides and phenolic chemicals. Challenges persist in enzyme cost, capacity, and regulatory barriers. Future studies should focus on optimizing enzyme combinations, increasing cost-efficiency through enzyme recycling, and combining enzymatic approaches with other green technologies to improve sustainability. Furthermore, broadening the spectrum of feedstocks and guaranteeing compliance with industry norms will be critical for widespread industrial use of enzyme-assisted procedures.

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INTRODUCTION

Plant bioresources, including agricultural residues, forestry byproducts, and food processing wastes, represent an abundant, renewable, and largely underutilized source of valuable biomolecules such as polyphenols, polysaccharides, proteins, lipids, and natural pigments (Abdelghany *et al.* 2020). The efficient utilization of these resources is increasingly recognized as a key pillar in advancing circular bioeconomy concepts, reducing environmental burdens associated with waste disposal, and promoting sustainable industrial development (Ugwu *et al.* 2025). Functional bioproducts derived from plant biomass exhibit a wide spectrum of biological and technological properties, including antioxidant, antibacterial, anti-inflammatory, and health-promoting activities, making them highly attractive for food, pharmaceutical, cosmetic, and nutraceutical applications (Estarriaga-Navarro *et al.* 2025). Despite their high potential, the recovery of bioactive compounds from plant bioresources is often limited by the complex and rigid architecture of plant cell walls, which restricts solvent penetration and hinders the release of intracellular compounds. Conventional extraction techniques frequently rely on high temperatures, extended processing times, and large volumes of organic solvents, which may lead to the degradation of thermolabile compounds, low selectivity, and increased environmental impact. These limitations have intensified the search for alternative, greener extraction technologies capable of improving extraction efficiency while preserving the structural integrity and bioactivity of target compounds (Lemoni *et al.* 2025).

Enzyme-assisted extraction has emerged as a promising green technology that effectively overcomes these constraints by selectively degrading structural polymers in plant cell walls under mild processing conditions (Jiang *et al.* 2025). In contrast to traditional solvent-based methods, enzymatic processes typically require lower solvent volumes, reduced energy consumption, and shorter extraction times, while offering higher selectivity toward specific biomolecules. Enzymes act as highly specific biocatalysts, enabling controlled hydrolysis of polysaccharides, proteins, and phenolic complexes without causing extensive chemical damage to sensitive bioactive compounds (Farhan *et al.* 2025). In recent years, enzyme-assisted valorization has gained increasing attention not only as an extraction technique, but also as an integrated strategy for sustainable biomass conversion within biorefinery frameworks. By facilitating the recovery of multiple high-value compounds from a single feedstock, enzymatic approaches align well with the principles of resource efficiency, waste minimization, and value-chain diversification. This makes enzyme-assisted extraction particularly relevant for the valorization of agro-industrial residues, which are generated in large quantities worldwide and often remain underexploited (Ntunka *et al.* 2025).

From a sustainability perspective, enzyme-assisted extraction supports regulatory and industrial demands for cleaner production technologies by minimizing the use of hazardous chemicals and reducing greenhouse gas emissions associated with energy-intensive processes (Díaz-de-Cerio and Trigueros 2025). Moreover, the compatibility of enzymatic processes with other green technologies—such as ultrasound, microwave, and membrane-assisted separations—offers additional opportunities for process intensification and performance enhancement (Roobab *et al.* 2025). Given the rapid expansion of research in this field, a comprehensive understanding of enzyme types, mechanisms of action, extraction efficiencies, application areas, and industrial feasibility is essential. This review therefore aims to provide an in-depth overview of enzyme-assisted valorization of plant bioresources, focusing on the types of enzymes employed, mechanistic pathways of extraction, applications in functional bioproduct development, industrial scale-up considerations, and comparative advantages over conventional and emerging extraction techniques. By addressing these interconnected aspects, this review highlights enzyme-assisted extraction as a key enabling technology for sustainable and high-value utilization of plant bioresources.

A thorough and structured literature review was used to evaluate recent improvements in enzyme-assisted biomass valorization. Major academic databases such as Web of Science, Scopus, PubMed, ScienceDirect, and Google Scholar were used to search for scientific papers. Enzyme-assisted extraction, biomass valorization, plant bioresources, hydrolytic enzymes, oxidative enzymes, and green extraction methods were some of the keywords and search strings used. To ensure relevance and scientific rigor, the literature was selected from peer-reviewed research articles, review papers, and book chapters published predominantly in the recent decade. Studies were selected based on their connection to enzyme types, extraction mechanisms, process efficiency, and their use in the food, pharmaceutical, cosmetic, and biorefinery industries. Papers that lacked adequate experimental description, were unrelated to plant-based biomass, or focused entirely on chemical extraction with no enzymatic involvement were eliminated. The chosen literature was thoroughly reviewed and structured to give a balanced and comprehensive overview of enzyme-assisted extraction methodologies, eliminating redundancy and stressing mechanistic understanding, technological improvements, and practical usefulness.

Enzymes in Biomass Valorization

Enzymes play a central role in biomass valorization due to their ability to selectively and efficiently catalyze the breakdown of complex plant cell wall components into valuable functional molecules. In enzyme-assisted extraction processes, enzymes act as biocatalysts that target specific structural and chemical bonds within plant biomass, thereby enhancing the release, solubilization, and accessibility of bioactive compounds. Based on their mode of action and substrate specificity, enzymes used in biomass valorization can be broadly classified into several major categories (Nargotra *et al.* 2023) as the following:

Hydrolytic enzymes

Hydrolytic enzymes, such as cellulases, hemicellulases, pectinases, and proteases, are essential for disrupting plant cell wall components such cellulose, hemicellulose, pectin, and protein scaffolding (Nofal *et al.* 2021; Al-Rajhi *et al.* 2022). Cellulases are multi-enzyme systems rather than single enzymes that play an important role in the enzymatic breakdown of cellulose. Most cellulases have a catalytic domain attached to a carbohydrate-binding module, which improves substrate affinity and catalytic efficiency. Cellulase systems function by combining multiple different enzymes to work together.

Endoglucanases randomly cleave internal β-1,4-glycosidic linkages in amorphous regions of cellulose, creating new chain ends and improving substrate accessibility (Schmitt and Hirakawa 2025). Exoglucanases, also known as cellobiohydrolases, act processively on the reducing or non-reducing ends of cellulose chains to release cellobiose units. β-Glucosidases convert cellobiose and short cello-oligosaccharides to glucose, avoiding product inhibition and completing cellulose saccharification (Mafa *et al.* 2025).

Hemicellulases, which include xylanases, mannanases, arabinofuranosidases, and acetylxylan esterases, work on the heterogeneous hemicellulose matrix. These enzymes have a variety of active-site designs that are specific to branched polysaccharides. Hemicellulases eliminate hemicellulosic barriers surrounding cellulose microfibrils, which improves total enzymatic accessibility and extraction efficiency (Dhakal *et al.* 2025).

Pectinases, which include polygalacturonases, pectin lyases, and pectin esterases, break down pectic compounds found largely in the middle lamella. The mechanism involves breaking of α-1,4-glycosidic and ester linkages, which leads to cell separation and increased porosity. Pectinases are especially crucial for converting fruit, vegetable, and soft biomass into valuable resources (Chandel *et al.* 2022).

Proteases catalyze the breakdown of peptide bonds in structural and storage proteins. They liberate protein-bound phenolics and bioactive peptides while also disrupting protein-polysaccharide complexes, hence enhancing extraction yield and functional characteristics (Oliveira *et al.* 2025).

Oxidative enzymes

Oxidative enzymes, such as laccases and peroxidases are oxidative enzymes that change phenolic structures and lignin constituents, leading to improved extractability and functional characteristics (Gałązka *et al.* 2025).

Glycoside hydrolases

Glycoside hydrolases, including β-glucosidase and α-amylase, target glycosidic bonds in cellulose, starch, and glycosylated phenolic compounds. These enzymes are crucial for releasing bound phenolics and oligosaccharides, enhancing both bioavailability and functional performance. Their application is especially relevant in biorefining processes and the production of functional food ingredients and nutraceuticals (Karnaouri *et al.* 2019).

Table 1. Types of Enzymes Employed in Biomass Valorization According to Substrate Specificity and Functional Role

Enzyme Type	Enzymes	Target Bio-molecules	Mechanism of Action	Applications	References
Hydrolytic enzymes	Cellulases, hemicellulases, pectinases, proteases	Cellulose, hemicellulose, pectin, proteins	Hydrolysis of polysaccharides, proteins	Release of sugars, polyphenols, peptides	(Łubek-Nguyen *et al.* 2022)
Oxidative enzymes	Laccases, peroxidases, tyrosinases	Phenolic compounds, lignin	Oxidation of phenolics and lignin	Enhancement of bioactive compound extraction	(Pham *et al.* 2024)
Glycoside hydrolases	β-glucosidase, α-amylase	Cellulose, starch	Hydrolysis of glycosidic bonds	Biorefining and functional food production	(Karnaouri *et al.* 2019)
Lipases	Lipases	Lipids, fats	Hydrolysis of ester bonds	Biocatalysis in biodiesel production and food	(Šelo *et al.* 2021)
Lignolytic enzymes	Lignin peroxidase, manganese peroxidase	Lignin	Lignin degradation	Waste valorization, biofuel production	(Vrsanska *et al.* 2016)

Lipolytic enzymes

Lipolytic enzymes, as lipases, are specialized enzymes that catalyze the hydrolysis of ester bonds in lipids and fats. In biomass valorization, lipases are employed to recover lipid-based compounds and to facilitate biocatalytic transformations in food, cosmetic, and biofuel applications. Their high specificity and efficiency under mild conditions make them valuable tools in sustainable lipid processing (Šelo *et al.* 2021).

Lignolytic enzymes

Lignolytic enzymes, including lignin peroxidase and manganese peroxidase, are primarily involved in lignin degradation. These enzymes disrupt the lignin network that protects cellulose and hemicellulose, thereby increasing the accessibility of carbohydrates and phenolic compounds. Lignolytic enzymes are particularly important in waste valorization and biofuel production, where extensive delignification is required Vrsanska *et al.* 2016). These enzymes' synergistic actions allows for the effective and selective release of important chemicals, making them indispensable instruments in enzyme-assisted biomass conversion (Mabate *et al.* 2025). The primary enzyme classes employed in biomass valorization, including their target substrates and functional roles summarized in (Table 1). Furthermore, the involvement of several enzymes in destroying biomass structural parts is depicted schematically in (Fig. 1).

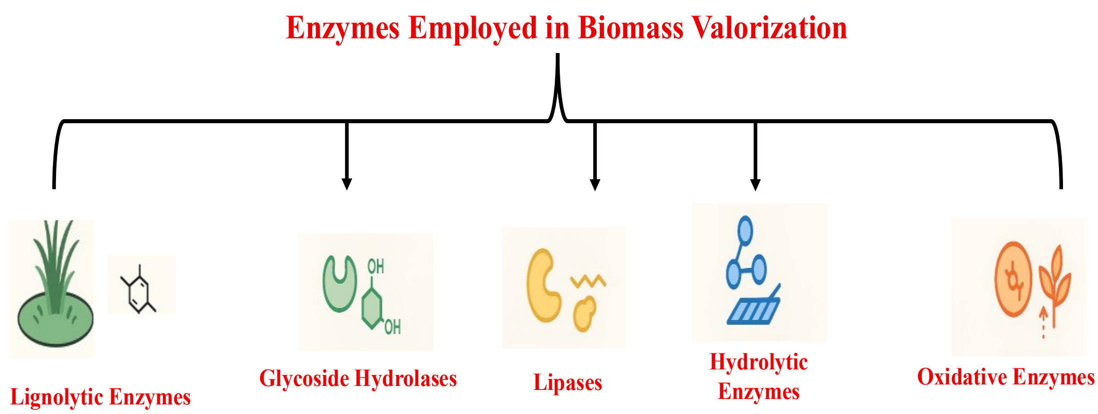

Fig. 1. Schematic representation of different enzyme–substrate interactions in biomass valorization processes

Mechanisms of Enzyme-Assisted Extraction

Enzyme-assisted extraction uses well-defined structural, molecular, and physico-chemical pathways to increase the release of intracellular and cell wall-bound bioactive chemicals from plant biomass. Unlike traditional extraction procedures, which rely mostly on solvent diffusion and heat effects, enzymatic extraction is driven by biocatalytic breakdown of specific plant cell wall constituents, resulting in controlled disintegration of biomass structures (Jiang *et al.* 2025). At the structural level, plant cell walls are made up of a complex network of cellulose microfibrils embedded in hemicellulose, pectin, lignin, and structural proteins, resulting in a stiff matrix that limits solvent accessibility. Enzymes including cellulases, hemicellulases, and pectinases selectively break down β-1,4-glycosidic bonds and ester connections in polymers. This focused hydrolysis enhances cell wall porosity, breaks the middle lamella, and reduces cell-cell adhesion, allowing solvent penetration and intracellular chemical diffusion (Xiao *et al.* 2025). At the molecular level, enzymatic reactions break down specific chemical bonds that attach bioactive chemicals to macromolecular matrices. β-glucosidases dissolve glycosidic bonds between phenolics and sugars, whereas proteases break protein-polyphenol and protein-polysaccharide complexes. These processes convert bound or insoluble chemicals into soluble, extractable forms while retaining their functional structure, therefore conserving bioactivity (Siddikey *et al.* 2025). From a mass transfer perspective, enzymatic degradation lowers diffusion barriers by reducing particle size, loosening polymeric networks, and expanding surface area. The increased solvent accessibility enhances solute migration from the solid matrix to the liquid phase. This mechanism explains why enzyme-assisted systems produce higher extraction yields and can have shorter processing times than non-enzymatic extraction (Segneanu *et al.* 2025). Enzymatic efficiency is also influenced by kinetic and process characteristics such as enzyme specificity, level, pH, temperature, substrate structure, and reaction time. Synergistic enzyme combinations frequently outperform single-enzyme systems in terms of cell wall disintegration because they target many structural components at the same time (Siddikey *et al.* 2025). Thus, enzyme-assisted extraction performs by selectively biocatalytically modifying plant biomass rather than causing non-specific physical disruption. This controlled mode of action allows for moderate processing conditions, higher selectivity, increased extraction efficiency, and the ongoing storage of thermolabile and bioactive chemicals, establishing enzymatic extraction as a machinery driven green technology (Jiang *et al.* 2025). Table 2 compiles important research that clarifies the mechanics behind enzyme-assisted extraction, such as mass transfer enhancement and cell wall disintegration. Additionally, Fig. 2 illustrates the primary molecular steps in enzyme-assisted extraction.

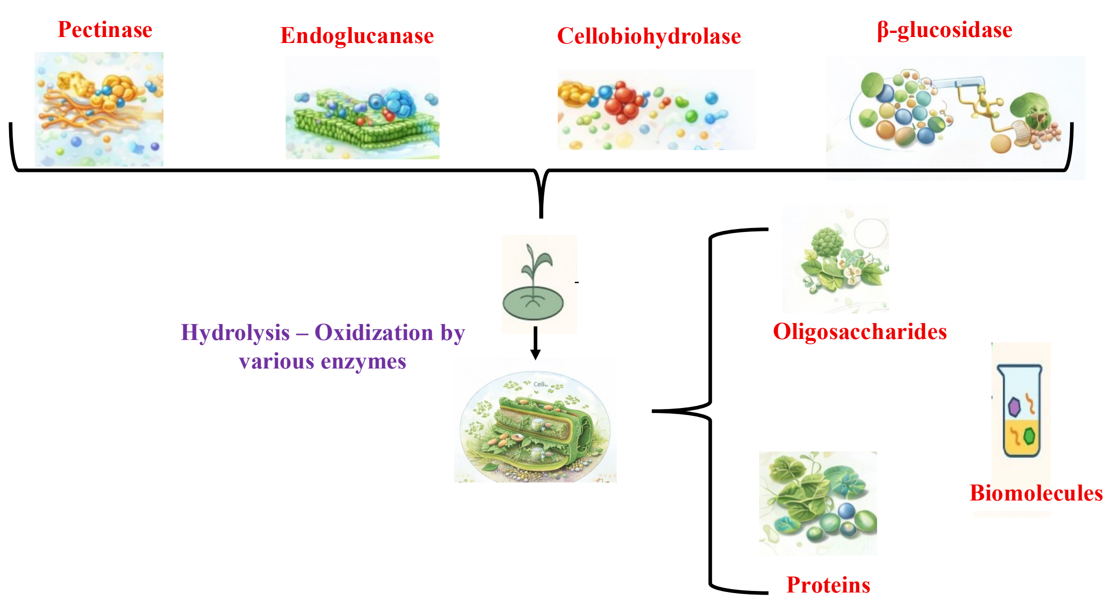

Fig. 2. Mechanistic pathways of enzyme-assisted extraction at the cellular and molecular levels

The synthesis of certain functional products *via* enzyme-assisted extraction is highly reliant on process parameters such as enzyme selection, enzyme combinations, temperature, pH, solid loading, and reaction time. Optimized enzyme cocktails are frequently required for synergistic hydrolysis of complicated biomass matrices. Mild temperatures (30 article 55 °C) and slightly acidic to neutral pH values (4.5 article 6.5) are commonly used to preserve enzyme activity while maintaining thermolabile substances. Solid loading and enzyme dosage have a substantial impact on extraction efficiency and process economics, necessitating careful optimization based on the intended product (Brienza *et al.* 2025). Some of the key references for enzyme-aided extraction conditions for various functional compounds are summarized in (Table 3).

Table 2. Summary of Representative Studies Investigating Mechanistic Pathways of Enzyme-Assisted Extraction

Plant Bioresource	**Enzymes Used**	**Target Compounds**	**Mechanism of action**	**Key Outcome**	**References**
Citrus peels	Pectinase, cellulase	Flavonoids, phenolic acids	Degradation of pectin-rich middle lamella and cellulose microfibrils	Enhanced phenolic yield and antioxidant activity	(Lima *et al.* 2025)
Grape pomace	Cellulase, hemicellulase, pectinase	Anthocyanins, tannins	Hydrolysis of polysaccharide network improving solvent penetration	Increased extraction efficiency and color stability	(Stanek-Wandzel *et al.* 2024)
Wheat bran	Xylanase, protease	Dietary fiber, bioactive peptides	Hemicellulose depolymerization and protein hydrolysis	Improved solubilization and functional properties	(Ren *et al.* 2024)
Soybean meal	Protease (Alcalase)	Bioactive peptides	Cleavage of protein–polyphenol complexes	Increased peptide yield and bioactivity	(Yan *et al.* 2022)
Apple pomace	Pectinase, cellulase	Pectins, phenolic compounds	Cell separation and loosening of cell wall structure	Higher recovery under mild processing conditions	(Kairė *et al.* 2025)
Olive leaves	Cellulase, β-glucosidase	Oleuropein, phenolics	Hydrolysis of glycosidic bonds releasing bound phenolics	Improved phenolic extraction and antioxidant capacity	(Huamán-Castilla *et al.* 2024)

Table 3. Enzyme-assisted Extraction Conditions for Different Functional Products

Target product	**Biomass source**	**Enzyme(s) used**	**Key conditions (pH, *T*, solid loading)**	**Main outcome**	**References**
Phenolics	Grape pomace	Pectinase + cellulase	pH 5.0, 45 °C, 5% solids	Phenolic yield	(Stanek-Wandzel *et al.* 2024)
Oligo-saccharides	Wheat bran	Xylanase	pH 6.0, 50 °C	Prebiotic oligo-saccharides	(Wu *et al.* 2025)
Sugars	Corn stover	Cellulase cocktail	pH 4.8, 50 °C	High glucose release	(Gong *et al.* 2020)
Proteins	Soy residue	Protease	pH 7.0, 40 °C	Bioactive peptides	(Mirzapour-Kouh-dasht *et al.* 2023)

Applications in Functional Bioproduct Production

The formation of functional bioproducts from a variety of plant bioresources has made extensive use of enzyme-assisted extraction (Streimikyte *et al.* 2022). Polyphenols, dietary fibers, bioactive peptides, and oligosaccharides with improved bioavailability and usefulness are recovered *via* enzymatic procedures in the food and nutraceutical industries (Zhao *et al.* 2025).

Enzyme-assisted extracts that are high in antioxidants, pigments, and polysaccharides are used in cosmetic formulations to prevent aging and protect the skin. Enzymes help extract plant-derived chemicals having antibacterial, anti-inflammatory, and anticancer characteristics for use in medicinal applications (Michalak 2023). Enzyme-assisted techniques also aid in the creation of useful components such natural thickeners, emulsifiers, and prebiotics. Enzymatic extraction frequently produces better-quality products with enhanced sensory and functional properties as compared to traditional methods (Zhao *et al.* 2025).

Enzyme-assisted valorization's adaptability underscores its promise as a crucial enabling technique for creating high-value functional bioproducts from plant-based feedstocks (Saorin Puton *et al.* 2025). The variety of functional bioproducts made with enzyme-assisted extraction, their source materials, and their intended uses are shown in (Table 4). Additionally, Fig. 3 summarizes the variety of uses made possible by enzyme-assisted extraction in the generation of functional bioproducts.

Table 4. Functional Bioproducts Obtained *via* Enzyme-assisted Extraction and their Corresponding Biomass Sources

Application Area	**Plant Bio-resource**	**Enzymes Used**	**Functional Bioproducts**	**Key Benefit**	**References**
Food & nutra-ceuticals	Grape pomace	Cellulase, pectinase	Polyphenols, anthocyanins	Enhanced antioxidant activity and bioavailability	Poblete *et al.* 2025
Food ingredients	Citrus peels	Pectinase	Pectin, flavonoids	Improved yield and functional properties	Lima *et al.* 2025
Nutra-ceuticals	Soybean meal	Protease (Alcalase)	Bioactive peptides	Increased peptide release and digestibility	Sedlar *et al.* 2025
Cosmetics	*Aloe vera*	Cellulase, hemicellulase	Polysaccharid es	Improved moisturizing and skin-protective properties	Elferjane *et al.* 2023
Pharma-ceuticals	Olive leaves	Cellulase, β-glucosidase	Oleuropein, phenolics	Increased antimicrobial and antioxidant activity	Vardakas *et al.* 2024
Functional fibers	Wheat bran	Xylanase	Soluble dietary fiber	Improved solubility and prebiotic potential	(Streimikyte *et al.* 2022)

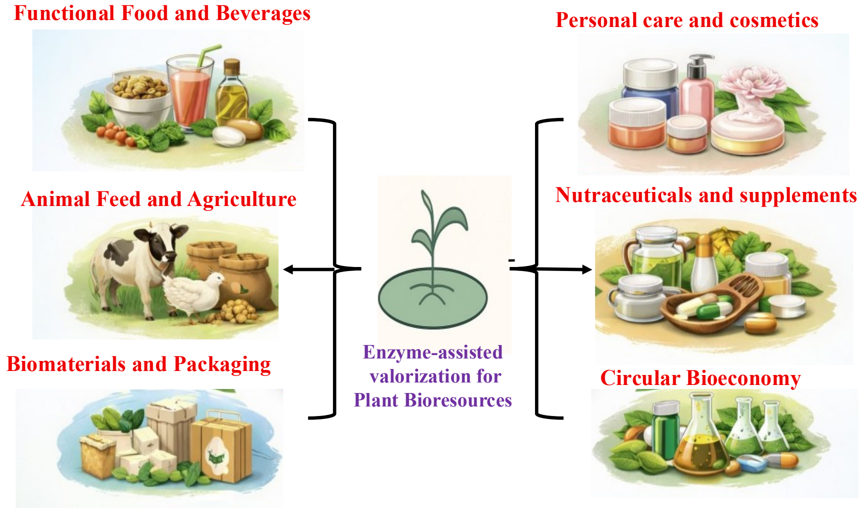

Fig. 3. Application spectrum of enzyme-assisted extraction in functional bioproduct development

Industrial Perspectives and Scale-Up

Reactor design, process integration, and operating parameters must all be carefully taken into account for the industrial application of enzyme-assisted extraction. Stirred-tank reactors, packed-bed reactors, and membrane-assisted systems are common reactor topologies that are chosen according to substrate properties and process scale (Palladino *et al.* 2024). The goal of process optimization is to maximize the efficiency of enzymes while reducing the expenses related to their manufacture, recovery, and reuse. Enzyme immobilization has drawn interest as a tactic to improve recyclability and operating stability (Mao *et al.* 2024).

Table 5. Industrial Implementation and Scale-Up Considerations for Enzyme-Assisted Extraction Technologies

Aspect	Description	Industrial Strategy	Advantage	References
Reactor type	Stirred-tank reactor	Batch or fed-batch enzymatic hydrolysis	Easy scale-up and process control	Arulrajah *et al.* 2025
Continuous processing	Packed-bed reactor	Immobilized enzymes	Enzyme reusability and reduced cost	Chalella Mazzocato & Jacquier 2024
Process optimization	Enzyme concentration, pH, temperature	Statistical and kinetic modeling	Improved efficiency and yield	López-Trujillo *et al.* 2023
Economic feasibility	Enzyme cost and recovery	Enzyme recycling and biorefinery integration	Lower operational cost	Ghinea *et al.* 2025
Sustainability	Reduced solvent and energy use	Green processing approach	Lower environmental footprint	Ibrahim *et al.* 2023
Regulatory compliance	Food/pharma-grade enzymes	GRAS approval and GMP standards	Market acceptance	Sutay Kocabaş & Grumet 2019

Enzyme-assisted procedures can be economically advantageous when incorporated into biorefineries that valorize several product streams. Sustainability assessments show reduced energy consumption, solvent usage, and environmental impact compared to typical extraction methods (Díaz-de-Cerio and Trigueros 2025). However, regulatory issues such as enzyme safety, product purity, and compliance with food and pharmaceutical standards remain significant hurdles. Addressing these variables is critical to successful industrial-scale adoption (Arnau *et al.* 2019). Table 5 presents industrial viewpoints such as scale-up problems, process integration, and economic considerations.

Comparative Analysis with Other Extraction Techniques

Enzyme-assisted extraction has various advantages over traditional solvent extraction and developing physical approaches including microwave-assisted, ultrasound-assisted, and pressured liquid extraction (Poblete *et al.* 2025). Conventional solvent extraction frequently necessitates huge volumes of organic solvents, high temperatures, and extended extraction times, which can result in thermolabile chemical degradation (Zhang *et al.* 2018). Microwave and ultrasound-assisted technologies improve mass transfer and minimize processing time, but they can induce localized heating and structural damage to sensitive bioactives (Mieles-Gómez *et al.* 2025). Pressurized liquid extraction enhances efficiency, but it requires a lot of energy and specialized equipment. In contrast, enzyme-assisted techniques operate under mild conditions with good selectivity, retaining the structural and functional integrity of target molecules (Poblete *et al.* 2025).

Table 6. Comparative Evaluation of Enzyme-Assisted and Conventional Extraction Techniques Based on Efficiency, Sustainability, and Product Quality

Extraction Technique	Operating Conditions	Advantages	Limitations	Comparison with Enzyme-Assisted Extraction	References
Conventional solvent extraction	High solvent, long time	Simple, low capital cost	Low selectivity, solvent residues	Less sustainable and lower product quality	Osorio- Tobó 2020
Microwave-assisted extraction	Rapid heating	Short extraction time	Thermal degradation risk	Enzymes offer milder conditions	Macedo *et al.* 2023
Ultrasound-assisted extraction	Acoustic cavitation	Improved mass transfer	Possible structural damage	Enzymes preserve bioactivity	Kenenbay *et al.* 2025
Pressurized liquid extraction	High pressure and temperature	High efficiency	High energy and equipment cost	Enzymes are more eco-friendly	Poblete *et al.* 2025
Enzyme-assisted extraction	Mild pH and temperature	High selectivity, green process	Enzyme cost	Superior sustainability and product integrity	Díaz-de-Cerio & Trigueros 2025

Enzymatic extraction is especially appealing for sustainable processing due to its lower environmental impact and enhanced product quality. Enzyme-assisted valorization is now considered as a better green extraction technology (Díaz-de-Cerio and Trigueros 2025). Table 6 compares enzyme-assisted extraction to conventional approaches.

Enzyme-assisted biomass valorization has a wide range of uses in industries such as food, pharmaceuticals, cosmetics, and biorefineries. The variety of functional products developed through specialized enzyme systems emphasizes the adaptability and technological maturity of enzymatic extraction technologies (Makaveckas *et al.* 2025). A comparative performance of extraction techniques in terms of yield, selectivity, and environment impact is found in (Table 7).

Table 7. Comparison of Extraction Techniques for Biomass Valorization

Extraction method	Yield (%)	Selectivity	Solvent use	Energy demand	Environ-mental impact	References
Conventional solvent	Low–moderate	Low	High	High	High	(Khalil *et al.* 2021)
Enzyme-assisted	High	High	Low	Moderate	Low	(Streimikyte *et al*. 2022)
Ultrasound-assisted	Moderate	Moderate	Moderate	Moderate	Moderate	(Chen *et al.* 2025)
Microwave-assisted	High	Low–moderate	Moderate	High	Moderate	(Laina *et al.* 2024)
Supercritical fluid	High	High	Low	Very high	Moderate	(Kamjam *et al.* 2024)

Despite the broad scope of this review, many limitations should be noted. First, the analysis is mostly based on published literature. Therefore, it is subject to the availability, quality, and reporting criteria of current studies. Differences in biomass sources, enzyme types, extraction conditions, and analytical procedures between research may prevent direct quantitative assessment of published work. Second, as laboratory-scale enzyme-assisted extraction procedures are extensively explored, there is less attention on pilot- and industrial-scale procedures due to a lack of publicly available data. Therefore, economic assessments and life-cycle analyses were not thoroughly reviewed because such data is inconsistently published in the literature. Finally, research published in languages other than English or with insufficient methodological detail were removed, which may have resulted in the exclusion of potentially important findings.

CONCLUSIONS AND FUTURE DIRECTIONS

1. Enzyme-assisted valorization is a sustainable and effective method for recovering high-value functional bioproducts from plant bioresources. Enzymatic methods improve extraction efficiency by selectively destroying plant cell wall components, while sensitive chemicals' structural integrity and bioactivity are preserved.

2. Hydrolytic and oxidative enzymes work together to convert biomass and release bioactive compounds such as polysaccharides, phenolics, and proteins under mild processing conditions. In terms of selectivity and environmental effect, enzyme-assisted extraction outperforms several traditional and developing extraction technologies due to its specificity and versatility.
3. Enzyme-assisted extraction improves product quality, reduces solvent and energy usage, and aligns with circular bioeconomy concepts in various industries, including food, pharmaceutical, cosmetic, and nutraceuticals.
4. Despite evident advantages, issues such as enzyme cost, process optimization, and regulatory compliance persist. Future advances in enzyme engineering, immobilization, and integration with other green technologies are projected to improve the industrial viability and scalability of enzyme-assisted biomass valorization.

Although problems such as optimization of processes, enzyme cost, and compliance with regulations persist (Saorin Puton *et al.* 2025), advances in technology for enzymes and biorefinery integration continue to increase the industrial applicability of enzyme-assisted extraction. Further investigation on enzyme-assisted extraction should concentrate on creating tailored enzyme combinations with increased specificity and synergistic efficacy against a variety of plant matrices. Improvements in enzyme engineering, immobilization methods, and recombinant production are projected to lower costs and increase operating stability on an industrial scale.

The combination of enzyme-assisted extraction with upcoming technologies such as ultrasonic or membrane separation may improve efficiency and selectivity (Abdel-Mageed 2025). Furthermore, life cycle evaluation and technological-economic analysis should be used systematically to analyze the sustainability and economic viability of enzymatic processes. Ramírez-Cando *et al.* (2025) suggest focusing on underutilized agro-industrial leftovers and unconventional plant bioresources to broaden the feedstock base for functional bioproduct development. Lastly, the harmonization of regulatory structures and uniform processing parameters will be required to support the widespread industrial implementation of enzyme-assisted valorization procedures.

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REFERENCES CITED

Abdelghany, T. A., Bakri, M. M., Al-Rajhi, A. M., Al Abboud, M. A., Alawlaqi, M. M., and Shater, A. R. M. (2020). "Impact of copper and its nanoparticles on growth, ultrastructure, and laccase production of *Aspergillus niger* using corn cobs wastes," *BioResources* 15(2), 3289-3306. https://doi.org/10.15376/biores.15.2.3289-3306

Abdel-Mageed, H. M. (2025). “Frontiers in nanoparticles redefining enzyme immobilization: A review addressing challenges, innovations, and unlocking sustainable future potentials,” *Micro and Nano Syst. Lett.* 13(7). https://doi.org/10.1186/s40486-025-00228-2

Al-Rajhi, A., Alharbi, A. A., Yahya, R., and Ghany, T. A. (2022). “Induction of hydrolytic enzyme production and antibiosis via a culture of dual fungal species isolated from soil rich with the residues of woody plants in Saudi Arabia,” *BioResources* 17(2), 2358-2371. https://doi.org/10.15376/biores.17.2.2358-2371

Arulrajah, P., Lievonen, A. E., Subaşı, D., Pagal, S., Weuster-Botz, D., and Heins A. L. (2025). “Scale-down bioreactors-comparative analysis of configurations,” *Bioprocess Biosyst Eng.* 48(10), 1619-1635. https://doi.org/10.1007/s00449-025-03182-w

Arnau, J., Yaver, D., and Hjort, C. M. (2019). “Strategies and challenges for the development of industrial enzymes using fungal cell factories,” *Grand Challenges in Fungal Biotechnology* 2019, 179-210. https://doi.org/10.1007/978-3-030-29541-7_7

Chalella Mazzocato, M., Jacquier, J. C. (2024). “Recent advances and perspectives on food-grade immobilisation systems for enzymes,” *Foods* 13(13), article 2127. https://doi.org/10.3390/foods13132127

Chandel, V., Biswas, D., Roy, S., Vaidya, D., Verma, A., and Gupta, A. (2022). “Current advancements in pectin: Extraction, properties and multifunctional applications,” *Foods*. 11(17), article 2683. https://doi.org/10.3390/foods11172683

Chen, W., Yu, D., Guan, L., and Cao, H. (2025). “Studies on the structure and properties of ultrasound-assisted enzymatic digestion of collagen peptides derived from *Chinemys reevesii* skin,” *Foods* 14(17), article 2960. https://doi.org/10.3390/foods14172960

Díaz-de-Cerio, E., and Trigueros, E. (2025). “Evaluating the sustainability of emerging extraction technologies for valorization of food waste: Microwave, ultrasound, enzyme-assisted, and supercritical fluid extraction,” *Agriculture* 15(19), article 2100. https://doi.org/10.3390/agriculture15192100

Dhakal, R., Guo, W., Vieira, R. A. M., Guan, L., and Neves, A. L. A. (2025). “Advances in lignocellulose-degrading enzyme discovery from anaerobic rumen fungi,” *Micro-organisms* 13(12), article 2826. https://doi.org/10.3390/microorganisms13122826

Elferjane, M. R., Jovanović, A. A., Milutinović, V., Čutović, N., Jovanović Krivokuća, M., and Marinković, A. (2023). “From *Aloe vera* leaf waste to the extracts with biological potential: Optimization of the extractions, physicochemical characterization, and biological activities,” *Plants* 12(14), article 2744. https://doi.org/10.3390/plants12142744

Estarriaga-Navarro, S., Valls, T., Plano, D., Sanmartín, C., and Goicoechea, N. (2025). “Potential application of plant by-products in biomedicine: From current knowledge to future opportunities,” *Antioxidants* 14(8), article 942. https://doi.org/10.3390/antiox14080942

Farhan, M., Hasani, I. W., Khafaga, D. S. R., Ragab, W. M., Ahmed Kazi, R. N., Aatif, M., Muteeb, G., and Fahim, Y. A. (2025). “ Enzymes as catalysts in industrial biocatalysis: Advances in engineering, applications, and sustainable integration,” *Catalysts*. 15(9), article 891. https://doi.org/10.3390/catal15090891

Gałązka, A., Jankiewicz, U., and Orzechowski, S. (2025). “The role of ligninolytic enzymes in sustainable agriculture: applications and challenges,” *Agronomy* 15(2), article 451. https://doi.org/10.3390/agronomy15020451

Ghinea, C., Ungureanu-Comăniță, E.-D., Țâbuleac, R. M., Oprea, P. S., Coșbuc, E. D., and Gavrilescu, M. (2025). "Cost-benefit analysis of enzymatic hydrolysis alternatives for food waste management," *Foods* 14(3), article 488. https://doi.org/10.3390/foods14030488

Gong, Z., Wang, X., Yuan, W., Wang, Y., Zhou, W., Wang, G., and Liu, Y. (2020). "Fed-batch enzymatic hydrolysis of alkaline organosolv-pretreated corn stover facilitating high concentrations and yields of fermentable sugars for microbial lipid production," *Biotechnol Biofuels*. 13, article 13. https://doi.org/10.1186/s13068-019-1639-9

Huamán-Castilla, N. L., Mamani Apaza, L. O., Zirena Vilca, F., Saldaña, E., Diaz-Valencia, Y. K., and Mariotti-Celis, M. S. (2024). "Comparative analysis of sustainable extraction methods and green solvents for olive leaf extracts with antioxidant and antihyperglycemic activities," *Antioxidants* (Basel). 13(12), article 1523. https://doi.org/10.3390/antiox13121523

Ibrahim, I. A., Khoo, K. S., Rawindran, H., Lim, J. W., Ng, H.-S., Shahid, M. K., Tong, W.-Y., Hatshan, M. R., Sun, Y.-M., Lan, J. C.-W., *et al.* (2023). "Environmental sustainability of solvent extraction method in recycling marine plastic waste," *Sustainability* 15(22), article 15742. https://doi.org/10.3390/su152215742

Jiang, Z., Chen, J., Guo, X., Chen, F., Guo, X., Wang, Q., and Jiao, B. (2025). "Mechanism and potential of aqueous enzymatic extraction for constructing green production system for lipids and proteins," *Foods* 14(23), article 3981. https://doi.org/10.3390/foods14233981

Kairė, A., Jagelavičiūtė, J., Bašinskienė, L., Syrpas, M., and Čižeikienė, D. (2025). "Influence of enzymatic hydrolysis on composition and technological properties of black currant (*Ribes nigrum*) pomace," *Applied Sciences* 15(11), article 6207. https://doi.org/10.3390/app15116207

Kamjam, M., Ngamprasertsith, S., Sawangkeaw, R., Charoenchaitrakool, M., Privat, R., Jaubert, J.-N., and Molière, M. (2024). "The great versatility of supercritical fluids in industrial processes: A focus on chemical, agri-food and energy applications," *Processes* 12(11), article 2402. https://doi.org/10.3390/pr12112402

Karnaouri, A., Matsakas, L., Krikigianni, E., Rova, U., and Christakopoulos, P. (2019). "Valorization of waste forest biomass toward the production of cello-oligosaccharides with potential prebiotic activity by utilizing customized enzyme cocktails," *Biotechnol. Biofuels*. 12, article 285. DOI: 10.1186/s13068-019-1628-z

Kenenbay, G., Chomanov, U., and Tursunov, A. (2025). "Ultrasound-assisted extraction enhances enzymatic activity and thermal stability of bovine pancreatin: Effect of pH and temperature," *Processes* 13(8), article 2511. https://doi.org/10.3390/pr13082511

Khalil, N., Bishr, M., El-Degwy, M., Abdelhady, M., Amin, M., and Salama, O. (2021). "Assessment of conventional solvent extraction vs. supercritical fluid extraction of khella (*Ammi visnaga* L.) furanochromones and their cytotoxicity," *Molecules*. 26(5), article 1290. https://doi.org/10.3390/molecules26051290

Laina, K. T., Drosou, C., Stergiopoulos, C., Eleni, P. M., and Krokida, M. (2024). "Optimization of combined ultrasound and microwave-assisted extraction for enhanced bioactive compounds recovery from four medicinal plants: Oregano, rosemary, hypericum, and chamomile,"*Molecules* 29, article 5773. https://doi.org/10.3390/molecules29235773

Lemoni, Z., Evangeliou, K., Lymperopoulou, T., and Mamma, D. (2025). "Incorporation of edible plant extracts as natural food preservatives: green extraction methods, antibacterial mechanisms and applications," *Foods* 14(23), article 4000. https://doi.org/10.3390/foods14234000

Lima, C. A., Contato, A. G., de Oliveira, F., da Silva, S. S., Hidalgo, V. B., Irfan, M., Gambarato, B. C., Carvalho, A. K. F., and Bento, H. B. S. (2025). "Trends in enzyme production from citrus by-products," *Processes* 13(3), article 766. https://doi.org/10.3390/pr13030766

López-Trujillo, J., Mellado-Bosque, M., Ascacio-Valdés, J. A., Prado-Barragán, L. A., Hernández-Herrera, J. A., and Aguilera-Carbó, A. F. (2023). "Temperature and pH optimization for protease production fermented by *Yarrowia lipolytica* from agro-industrial waste," *Fermentation* 9(9), article 819. https://doi.org/10.3390/fermentation9090819

Łubek-Nguyen, A., Ziemichód, W., and Olech, M. (2022). Application of enzyme-assisted extraction for the recovery of natural bioactive compounds for nutraceutical and pharmaceutical applications," *Applied Sciences* 12(7), article 3232. https://doi.org/10.3390/app12073232

Mabate, B., Mkabayi, L., Goddard, D. R., Grobler, C. E., and Pletschke, B. I. (2025). "Role of enzyme technologies and applied enzymology in valorising seaweed bioproducts," *Marine Drugs* 23(8), article 303. https://doi.org/10.3390/md23080303

Macedo, G. A., Barbosa, P. P. M., Dias, F. F. G., Crawford, L. M., Wang, S. C., and Bell, J. M. L. N. M. (2023). "Optimizing the integration of microwave processing and enzymatic extraction to produce polyphenol-rich extracts from olive pomace," *Foods* 12(20), article 3754. https://doi.org/10.3390/foods12203754

Mafa, M. S., Pletschke, B. I., and Malgas, S. (2021). "Defining the frontiers of synergism between cellulolytic enzymes for improved hydrolysis of lignocellulosic feedstocks,: *Catalysts* 11(11), article 1343. https://doi.org/10.3390/catal11111343

Makaveckas, T., Šimonėlienė, A., and Šipailaitė-Ramoškienė, V. (2025). "Lignin valorization from lignocellulosic biomass: Extraction, depolymerization, and applications in the circular bioeconomy," *Sustainability* 17(21), article 9913. https://doi.org/10.3390/su17219913

Mao, S., Jiang, J., Xiong, K., Chen, Y., Yao, Y., Liu, L., Liu, H., and Li. X. (2024). "Enzyme engineering: Performance optimization, novel sources, and applications in the food industry," *Foods* 13(23), article 3846. https://doi.org/10.3390/foods13233846

Michalak, M. (2023). "Plant extracts as skin care and therapeutic agents," *Int. J. Mol. Sci.* 24(20), article 15444. https://doi.org/10.3390/ijms242015444

Mieles-Gómez, L., Quintana, S. E., and García-Zapateiro, L. A. (2025). "Comparison of ultrasound- and microwave-assisted extraction techniques on chemical, technological, rheological, and microstructural properties of starch from mango kernel," *Gels* 11(5), article 330. https://doi.org/10.3390/gels11050330

Mirzapour-Kouhdasht, A., McClements, D. J., Taghizadeh, M. S., Niazi, A., and Garcia-Vaquero, M. (2023). "Strategies for oral delivery of bioactive peptides with focus on debittering and masking," *NPJ Sci. Food*. 7(1), article 22. https://doi.org/10.1038/s41538-023-00198-y

Nargotra, P., Sharma, V., Lee, Y.-C., Tsai, Y.-H., Liu, Y.-C., Shieh, C.-J., Tsai, M.-L., Dong, C.-D., and Kuo, C.-H. (2023). "Microbial lignocellulolytic enzymes for the effective valorization of lignocellulosic biomass: A review," *Catalysts* 13(1), article 83. https://doi.org/10.3390/catal13010083

Nofal, A. M., El-Rahman, M. A., Abdelghany, T. M., and Mahmoud, A. E . (2021). "Mycoparasitic nature of Egyptian *Trichoderma* isolates and their impact on suppression *Fusarium* wilt of tomato," *Egyptian Journal of Biological Pest Control* 31, 1-8. https://doi.org/10.1186/s41938-021-00450-1

Ntunka, M. G., Makhathini, T. P., Khumalo, S. M., Bwapwa, J. K., Tshibangu, M. M. (2025). "Recent developments in the valorization of sugarcane bagasse biomass via integrated pretreatment and fermentation strategies,"*Fermentation*. 11(11), article 632. https://doi.org/10.3390/fermentation11110632

Oliveira, T. S. d. C., Gusmão, J. V. F., Rigolon, T. C. B., Wischral, D., Campelo, P. H., Martins, E., and Stringheta, P. C. (2025). "Bioactive compounds and the performance of proteins as wall materials for their encapsulation," *Micro*. 5(3), article 36. https://doi.org/10.3390/micro5030036

Osorio-Tobón, J. F..(2020). "Recent advances and comparisons of conventional and alternative extraction techniques of phenolic compounds," *J. Food Sci. Technol*. 57(12), 4299-4315. https://doi.org/10.1007/s13197-020-04433-2

Palladino, F., Marcelino, P. R. F., Schlogl, A. E., José, Á. H. M., Rodrigues, R. d. C. L. B., Fabrino, D. L., Santos, I. J. B., and Rosa, C. A. (2024). "Bioreactors: Applications and innovations for a sustainable and healthy future—A critical review," *Applied Sciences* 14(20), article 9346. https://doi.org/10.3390/app14209346

Pham, T. N., Cazier, E. A., Gormally, E., and Lawrence, P. (2024). "Valorization of biomass polyphenols as potential tyrosinase inhibitors," *Drug Discov. Today* 29(1), article 103843. https://doi.org/10.1016/j.drudis.2023.103843

Poblete, J., Aranda, M., and Quispe-Fuentes, I. (2025). "Efficient conditions of enzyme-assisted extractions and pressurized liquids for recovering polyphenols with antioxidant capacity from pisco grape pomace as a sustainable strategy," *Molecules* 30(14), article 2977. https://doi.org/10.3390/molecules30142977

Ramírez-Cando, L. J., Mora-Ochoa, Y. I., Freire-Sanchez, A. S., Medina-Rodriguez, B. X. (2025). "Life cycle sustainability assessment of agriproducts in Latin America: Overview based on latent dirichlet allocation," *Sustainability* 17(11), article 4954. https://doi.org/10.3390/su17114954

Ren, H., Wang, T., and Liu, R. (2024). "Correlation analyses of amylase and protease activities and physicochemical properties of wheat bran during solid-state fermentation," *Foods* 13(24), article 3998. https://doi.org/10.3390/foods13243998

Roobab, U., Aadil, R. M., Kurup, S. S., and Maqsood, S. (2025). "Comparative evaluation of ultrasound-assisted extraction with other green extraction methods for sustainable recycling and processing of date palm bioresources and by-products: A review of recent research," *Ultrason Sonochem*. 114, article 107252. https://doi.org/10.1016/j.ultsonch.2025.107252

Saorin Puton, B. M., Demaman Oro, C. E., Lisboa Bernardi, J., Exenberger Finkler, D., Venquiaruto, L. D., Dallago, R. M., and Tres, M. V. (2025). "Sustainable valorization of plant residues through enzymatic hydrolysis for the extraction of bioactive compounds: Applications as functional ingredients in cosmetics," *Processes* 13(5), article 1314. https://doi.org/10.3390/pr13051314

Sedlar, T., Pasković, I., Dragojlović, D., Popović, S., Vidosavljević, S., Goreta Ban, S., and Popović, L. (2025). "Enzyme-assisted extraction of proteins from cauliflower and broccoli waste leaves," *Horticulturae* 11(2), article 148. https://doi.org/10.3390/horticulturae11020148

Segneanu, A. E., Bejenaru, L. E., Bejenaru, C., Blendea, A., Mogoşanu, G. D., Biţă, A., and Boia, E. R.. (2025). "Advancements in hydrogels: A comprehensive review of natural and synthetic innovations for biomedical applications," *Polymers*. 17(15), article 2026. https://doi.org/10.3390/polym17152026

Šelo, G., Planinić, M., Tišma, M., Tomas, S., Koceva Komlenić, D., and Bucić-Kojić, A. (2021). "A comprehensive review on valorization of agro-food industrial residues by solid-state fermentation," *Foods* 10(5), article 927. https://doi.org/10.3390/foods10050927

Schmitt, K. K. I., and Hirakawa, H. (2025). "Assembly of cellulases from separate catalytic domains and a cellulose-binding module for understanding cooperative crystalline cellulose degradation," *Applied Sciences* 15(4), article 2214. https://doi.org/10.3390/app15042214

Siddikey, F., Jahan, M. I., Hormoni, Hasan, M. T., Nishi, N. J., Hasan, S. M. K., Rahman, N., Al Faik, M. A., and Hossain, M. A. (2025). "Enzyme technology in the food industry: Molecular mechanisms, applications, and sustainable innovations," *Food Sci Nutr*. 13(9), article e70927. https://doi.org/10.1002/fsn3.70927

Stanek-Wandzel, N., Krzyszowska, A., Zarębska, M., Gębura, K., Wasilewski, T., Hordyjewicz-Baran, Z., and Tomaka, M. (2024). "Evaluation of cellulase, pectinase, and hemicellulase effectiveness in extraction of phenolic compounds from grape pomace," *International Journal of Molecular Sciences* 25(24), article 13538. https://doi.org/10.3390/ijms252413538

Streimikyte, P., Viskelis, P., and Viskelis, J. (2022). "Enzymes-assisted extraction of plants for sustainable and functional applications," *Int. J. Mol. Sci*. 23(4), article 2359. https://doi.org/10.3390/ijms23042359

Ugwu, C. O., Berry, M. D., and Winans, K. S. (2025). "Advancing bioresource utilization to incentivize a sustainable bioeconomy: A systematic review and proposal of the enhanced bioresource utilization index," *Processes* 13(9), article 2822. https://doi.org/10.3390/pr13092822

Vardakas, A., Kechagias, A., Penov, N., and Giannakas, A. E. (2024). "Optimization of enzymatic assisted extraction of bioactive compounds from *Olea europaea* leaves," *Biomass* 4(3), 647-657. https://doi.org/10.3390/biomass4030035

Vrsanska, M., Voberkova, S., Langer, V., Palovcikova, D., Moulick, A., Adam, V., and Kopel, P. (2016). "Induction of laccase, lignin peroxidase and manganese peroxidase activities in white-rot fungi using copper complexes," *Molecules* 21(11), article 1553. https://doi.org/10.3390/molecules21111553

Wu, Y., Liu, C., Qiu, Q., and Zhao, X. (2025). "Xylo-oligosaccharide production from wheat straw xylan catalyzed by a thermotolerant xylanase from rumen metagenome and assessment of their probiotic properties," *Microorganisms* 13(11), article 2602. https://doi.org/10.3390/microorganisms13112602

Xiao, P., Yarava, J. R., Debnath, D., Sahu, P., Xu, Y., Xie, L., Holmes, D., and Wang, T. (2025). "Rapid high-resolution analysis of polysaccharide-lignin interactions in secondary plant cell walls using proton-detected solid-state NMR," *Anal. Chem*. 97(33), 18046-18054. https://doi.org/10.1021/acs.analchem.5c02059

Yan, F., Wang, Q., Teng, J., Wu, F., and He, Z. (2022). "Preparation process optimization and evaluation of bioactive peptides from *Carya cathayensis* Sarg meal," *Curr. Res. Food Sci*. 6, article 100408. https://doi.org/10.1016/j.crfs.2022.100408

Zhang, Q. W., Lin, L. G., and Ye, W. C. (2018). "Techniques for extraction and isolation of natural products: A comprehensive review," *Chin. Med*. 13, article 20. https://doi.org/10.1186/s13020-018-0177-x

Zhao, L., Ju, W. M., Wang, L. L., Ye, Y. B., Liu, Z. Y., Cavender, G., Sun, Y. J., and Sun, S. Q. (2025). "Functional ingredients: From molecule to market – AI-enabled design, bioavailability, consumer impact, and clinical evidence," *Foods* 14(17), article 3141. https://doi.org/10.3390/foods14173141

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