Scientific Bulletin. Series F. Biotechnologies, Vol. XXIX, No. 2, 2025
ISSN 2285-1364, CD-ROM ISSN 2285-5521, ISSN Online 2285-1372, ISSN-L 2285-1364

RESEARCH ON THE VALORIZATION OF BY-PRODUCTS AND/OR WASTES FROM *BRASSICA OLERACEA* - A REVIEW

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Abstract

Managing vegetable waste and by-products is a worldwide challenge for the agricultural sector. As a widely consumed vegetable crop, Brassica oleracea (B. oleracea) accounts for a higher volume of waste in the supply chain process, with cabbage, cauliflower, broccoli, and kale accounting for a significant share. Therefore, the sustainable and resource-efficient use of waste is essential. This review examines the potential applications of B. oleracea waste and by-products, with particular attention to cabbage, cauliflower, broccoli, and kale in food, pharmaceutical, and other sectors. The importance of their use in value-added applications is addressed, with emphasis on key biomolecules, technologies involved in the valorisation process, and future aspects of practical applications. Cabbage, broccoli, and cauliflower produce waste and by-products that are not processed, including leaves, stems, stalks, and roots. Most of these contain high-value biomolecules, including bioactive plant proteins and phytochemicals, glucosinolates, flavonoids, anthocyanins, carotenoids, and tocopherols. Interestingly, isothiocyanates derived from glucosinolates have potent anti-inflammatory and anti-cancer properties by different interactions with cellular molecules and modulation of key cellular signalling pathways. Therefore, these B. oleracea residues can be efficiently valued using different innovative extraction and biotransformation techniques and the use of different biorefining approaches. This not only minimizes the environmental impact but also helps to develop products with high-added value for food, pharmaceutical, and other related industries.

Key words: *Brassica oleracea, green extraction methods, phytochemicals sustainable bioconversion, waste valorisation.*

INTRODUCTION

Agro-industrial waste production has surged because of rapid developments in global agricultural and food production which has led to dangerous resource mismanagement alongside economic loss while impacting the environment (Singh et al., 2021). *B. oleracea* vegetables that include Brussels sprouts alongside cabbage, cauliflower, broccoli, kale and other species constitute the primary source of this waste material (Shinali et al., 2024).

These vegetables receive widespread cultivation and consumption across the global market, but processing operations lead to substantial waste production of stems and leaves and cores and outer layers that end up as discards. Waste materials that people commonly discard present a rising danger to food systems even though they contain unutilized beneficial bioactive substances (Vilas-Boas et al., 2021).

There are numerous sources from studies of compounds that are rich in phytochemicals such as glucosinolates, phenolics, flavonoids, vitamins, minerals, and dietary fibres, all of which have very strong antioxidants, antimicrobial, anti-inflammatory, and anticancer properties (Dillard & German, 2000). The invention brought the field of waste use into a new direction, accentuating the urgency of converting food remnants into valuable products. Considering this, there is growing interest in creating environmentally friendly methods for recovering and using these compounds from *B. oleracea* waste streams to support the circular economy (Ungureanu et al., 2022).

The research aims to investigate *B. oleracea* crop biomass waste together with its recent developments in transformation processes. The review presents modern green extraction methods such as microwave-assisted extraction together with ultrasound extraction and supercritical fluids and bioconversion techniques including fermentation and pyrolysis (Usman et al., 2023). The conversion methods allow producers to turn vegetable waste into multiple usable products that range from pharmaceuticals to cosmetics and nutraceuticals to biofuels and packaging materials. Resource-efficiency innovations and environmental reduction and economic development follow from how the review finds profitable applications for vegetable waste (Damian et al., 2024). The review provides both governments and researchers with knowledge about how to convert waste materials into monetary value through sustainable technologies.

This review provides an updated assessment of different methods for by-products of *B. oleracea* valorisation that extends beyond previous individual studies. The analysis shows both biological properties of materials and technical advancements which enable their recovery for utilization. The research explains how difficult it is for regulatory requirements while challenging the production of standardized products and large-scale process implementation.

The current investigation broadens existing sustainable waste management research through studies of under-explored *B. oleracea* waste handling methods. This article provides informations about sustainable creation techniques while presenting contemporary environmental insights thus bringing new conceptual worth through its combination of biological economic principles with practical applications.

PHYTOCHEMICAL PROFILING AND VALORIZATION POTENTIAL OF *B. OLERACEA*

The nutritional value of *B. oleracea* vegetables keeps scientists busy because they want to study both the edible portions as well as the valuable bioactive compounds in processing residues (Favela-González et al., 2020). The main consumption of primary products consists of using florets, heads or leaves yet significant biomass remains underutilized through the excess of stalks, roots and peelings and trimmings. Science has identified discarded parts as storage areas for beneficial phytochemicals which are currently underutilized in present-day food systems (Waraczewski et al., 2022).

Scientific research into *B. oleracea* waste has discovered multiple secondary metabolites, which demonstrate strong nutraceutical value and therapeutic properties. The phytochemical profiling of *B. oleracea* is given in Table.1. The vegetable's chemical structure contains glucosinolates that produce sulforaphane and indole-3-carbinol along with flavonoids kaempferol and quercetin and different phenolic acids and carotenoids. The therapeutic potential of these compounds includes free-radical protection as well as anti-inflammatory action and carcinogenic pathway disruption hence producing valuable substances for preventative medicine (Mittal et al., 2025).

The bioactive compound content and chemical makeup differs based on plant sections along with plant variety and both environmental variables and post-gathering treatment techniques. Solutions derived from broccoli stems contain stronger glucosinolate concentrations than parts from the leaves, but red cabbage waste contains abundant anthocyanin compounds. Compositional profiling stands essential because of its ability to demonstrate the importance of developing targeted valorisation strategies (Gudiño et al., 2024).

The valorisation potential of these compounds has increased due to research on environmentally friendly techniques to extract them. The extraction techniques follow guidelines of green chemistry and help create environmentally friendly processing methods for turning agro-industrial waste into new products (Freitas et al., 2021). These phytochemicals extracted from waste products possess various unique commercial uses. Functional food industry team members extract phytochemicals from plant materials to increase product nutritional value and to provide antimicrobial protection (da Silva et al., 2016). Manufacturers integrate *B. oleracea* extracts into beauty products, which protect the skin and address signs of aging and provide UV defence. Phytochemicals from *B. oleracea* enter dietary supplement markets more frequently because they help supporters of immune health and supporters of chronic disease prevention (Šamec et al., 2017).

Table.1 Phytochemical Profiling of *B.* oleracea (Valisakkagari et al., 2024)

By-product source	Phytochemicals	Health Benefits	Extraction/ bioprocessing method	End-use applications
Broccoli stems & stalks	Glucosinolates, isothiocyanates	Anticancer, detoxification	Enzymatic hydrolysis, MAE	Functional foods, pharmaceuticals
Red cabbage outer leaves	Anthocyanins, vitamin C, phenolics	Antioxidants, skin protection	Solvent extraction, UAE	Cosmetics, antioxidant supplements
Cauliflower trimmings	Flavonoids (kaempferol, quercetin)	Cardiovascular support, anti-inflammatory	UAE, SFE, deep eutectic solvents	Nutraceuticals, food preservatives
Kale stems	Lutein, β-carotene, dietary fibre	Eye health, digestion	Pressurized liquid extraction	Fortified foods, dietary supplements
Brussels sprouts peels	Indoles, sinapic acid, minerals	Hormone balance, bone health	Fermentation, aqueous extraction	Herbal products, mineral-enriched beverages
Cabbage outer layers	Tannins, vitamin K, glucobrassicin	Blood clotting support, anti-infective	Microwave-assisted extraction	Medical formulations, cosmeceutical emulsions

Through microbial fermentation methods the targeted compounds benefit from both bioavailability and functionality improvement after direct extraction. Laboratory studies demonstrated that fermentation of cabbage waste resulted in better antioxidant effects than raw materials because the fermentation process converted bound phenolic compounds into free phenolic compounds (Dey et al., 2016). The expanding worldwide interest in sustainable resources makes the phytochemical value of *B. oleracea* by-products an enduring reason to promote their recovery and circular economic implementation (Berndtsson, 2019). Value-added use of these waste products simultaneously decreases environmental impacts while generating economic business possibilities within food systems and healthcare and cosmetics industries. Research must continue to enhance extraction procedures along with ensuring product stability as well as developing commercial-scale deployment of these innovations (Makepa & Chihobo, 2024).

ECO-FRIENDLY EXTRACTION TECHNOLOGIES

The development of environmentally friendly extraction technologies for *B. oleracea* by-products has increased in popularity during recent years (Mittal et al., 2025). These sustainable approaches allow businesses to obtain valuable compounds from agricultural residues by reducing the environmental impacts of established procedures. Traditional solvent extractions that use organic solvents trigger numerous environmental issues because they use significant hazardous chemicals along with high energy consumption (Clarke et al., 2018). The alternative eco-friendly techniques deliver sustainable approaches that maintain thermos-labile phytochemicals while providing cost-effective scalable operations (More et al., 2022).

Microwave-assisted extraction (MAE)

Microwave-assisted extraction utilizes microwave radiation to heat both plant materials and solvent rapidly that leads to plant cell wall disruption and enhanced transport of polyphenols and flavonoids together with glucosinolates (López-Salazar et al., 2023). Increasing temperatures through MAE reduces extraction duration and needs fewer solvents than ordinary extraction procedures. Users have used this process to obtain antioxidant-rich compounds from broccoli stems and cabbage leaves which show promise for pharmaceutical and food industries and nutraceutical applications (Muzaffar et al., 2025).

Ultrasound-assisted extraction (UAE)

Ultrasonic cavitation applies disturbances to plant tissues in UAE allowing bioactive elements to escape. When bubbles form and burst inside the solvent solution, they make cell walls more permeable thus increasing diffusion speed (Chemat et al., 2017). UAE works at mild temperature conditions suitable for extracting thermally sensitive molecules and successfully recovers glucosinolates and phenolic compounds from vegetable waste materials. The energy-efficient operation and shorter processing duration of this technology make it suitable for running sustainable extraction at large scales (Wang, 2014).

Supercritical fluid extraction (SFE)
Lipophilic compound extraction from *B. oleracea* waste happens through SFE methods which utilizes carbon dioxide (CO_2) as a solvent. The combination of gas and liquid properties in supercritical CO_2 enables the substance to penetrate plant cells effectively which results in efficient compound dissolution. SFE functions as a selective method to produce pure solvent-free product extracts needed by food and cosmetics manufacturers. The process successfully recovers phytosterols as well as carotenoids and volatile oils from broccoli florets and cabbage outer layers thus increasing their viability in natural product development (Nartea, 2022).

Extraction with deep eutectic solvent (DES)
Extraction with deep eutectic solvents (DES) establish themselves as a new sustainable method. Natural biodegradable components that include sugars amino acids and organic acids from DES allow the formation of solvents which have adjustable polarity and solvation characteristics. DES optimally to extract both glucosinolates and flavonoids from cauliflower leaves and kale residues because of their specific polar features. DES represent an environmentally conscious choice because they possess both low toxicity and high biodegradability features while remaining suitable for sustainable food-grade and pharmaceutical extractions (Chemat et al., 2019).

BIOCONVERSION AND PROCESSING APPROACHES

Environmental sustainability demands and resource conservation practices drive scientists to find bioconversion process methods that transform agricultural waste into useful products. The discarded *B. oleracea* agricultural residue after harvest contains many bioactive elements that scientists can extract through developed biotechnological approaches. Cruciferous vegetable residue utilization reaches its maximum potential through the sustainable bioconversion methods that include microbial fermentation and thermochemical pyrolysis for establishing circular economic systems (Vasileiadou, 2024).

Fermentation
Natural fermentation allows efficient improvement of *B. oleracea* by-products nutrition along with functional characteristics through beneficial processes. The biological transformation of complex plant structures by *Lactobacillus, Saccharomyces* or fungal microorganisms leads to the release of bioactive compounds and their subsequent bioavailability increase. Enzymes present during fermentation convert glucosinolates into beneficial isothiocyanates that demonstrate strong anticancer properties and antioxidant effects (Ogrodowczyk & Drabińska, 2021). The production of phenolic-rich extracts along with probiotics combined with organic acids such as lactic acid and acetic acid and functional enzymes occur when solid-state and submerged fermentation methods are employed. Through fermentation, anti-nutritional elements from plant materials decrease while digestibility increases thus enabling producers to create dietary supplements and fermented beverages and animal feed products. Scientists have shown statistically that fermentation of broccoli and cabbage waste leads to increased antioxidant properties that will serve as ingredients in new food products. The process becomes a valuable addition to vegetable waste while perfectly accommodating clean-label and health-oriented consumer choices in the food and nutraceutical industries (Mamia, 2023).

Pyrolysis and thermochemical conversion
The conversion of *B. oleracea* biomass through thermochemical methods including pyrolysis provides an effective process to obtain energy and functional materials. Organic material decomposition during pyrolysis creates three main products which are bio-oil and syngas (synthetic gas) together with biochar. The

several products derived from this process possess meaningful applications in industrial sectors. The refinement of bio-oil allows its conversion to renewable fuel or chemical materials whereas syngas supports heat and power applications while biochar functions as an effective soil amendment capable of capturing carbon. *B. oleracea* residue consists of substantial lignocellulosic material which makes it an ideal source for thermochemical processing (Paudel et al., 2024). The pyrolysis and gasification methods provide improved control of final products while producing processes which result in reduced atmospheric emissions of greenhouses gases. The waste management solution and sustainable energy delivery system provide optimal results by utilizing vegetable residues which are easily accessible in rural and agro-industrial areas. The process efficiency of catalytic pyrolysis and integrated bio-refinery systems has reached a point where premium compounds like furans and aldehydes alongside bio-based solvents can be derived from vegetable waste. Bioconversion technologies integrated for *B. oleracea* by-products valorisation present a beneficial solution to achieve sustainable waste management. Fermentation and thermochemical conversion provide sustainable methods which support bioeconomic development along with environmental sustainability and complete agricultural resource utilization (Uddin et al., 2025).

HIGH-VALUE APPLICATIONS FOR *B. OLERACEA* WASTE

The utilization of *B. oleracea* waste provides multiple economic opportunities which enable manufacturers to develop products of value for food sectors and pharmaceuticals and cosmetics production together with applications in energy generation and material packaging (Castelão-Baptista et al., 2021). Research indicates that the waste parts of broccoli, cabbage, cauliflower and kale vegetables can be used to obtain high-value products due to their phytochemical content and fibrous structure. The waste products from industrial processes are recognized today as sustainable raw materials which lead to economically beneficial and usable end products (Oleszek et al., 2023).

Nutraceuticals and functional foods

The processing of *B. oleracea* by-products represents a vital opportunity within the nutraceutical industry for producing functional foods. The high glucosinolate, flavonoid, polyphenol and vitamin content of *B. oleracea* allows the production of nutritious food products for maintaining human health beyond essential dietary needs (Quizhpe et al., 2024). The antioxidant and anti-inflammatory properties along with cholesterol-lowering effects are obtainable through extracts from cabbage or broccoli would become integral components of dietary supplements and beverages as well as snacks and teas. Fermentation together with drying methods permit bioactive compounds to become highly concentrated while preserving their form suitable for manufacturing commercially available food items. The rising market need for natural health improvement ingredients transforms cruciferous vegetable wastes into an important raw material for functional food design (García-González et al., 2025).

Cosmeceuticals

The cosmeceutical industry has established *B. oleracea* by-products as important plant material for developing skincare and personal care products. Science demonstrates that extracted compounds from cabbage and broccoli residual matter work as protective agents against UV radiation and biochemical skin damage and skin aging. The properties of cabbage or broccoli residues are used to develop natural serums and creams and sunscreen products that combat aging skin. Consumer interest in organic cosmetics with clean-label ingredients led to vegetable waste adoption as an environmentally friendly substitute for synthetic beauty products within the personal care sector (Saharan, 2023).

Biofuels and bioenergy

B. oleracea waste gets extensively utilized for renewable energy production. The biofuel products biodiesel along with bioethanol and biogas can be made by processing lignocellulosic biomass found in vegetable stems and leaves using biochemical and thermochemical conversion methods (Vasileiadou, 2024). Through anaerobic digestion and transesterification and pyrolysis methods organic waste becomes energy carriers which replace traditional fossil fuel types in an eco-friendly manner. This method enables waste reduction while simultaneously contributing to the development of decentralized power systems for distant communities especially where vegetable waste accumulation from agriculture is high (Herran & Nakata, 2012).

Biodegradable packaging and industrial materials

B. oleracea by-products contain suitable structures that enable their use in industrial production of eco-friendly materials and biodegradable packaging solutions. The production of sustainable alternative plastic packaging becomes possible through the addition of vegetable fibres to bioplastics and polymer blends (Gómez-Gast et al., 2022). Biodegradable materials from these by-products together achieve dual benefits by serving as sustainable replacements for petroleum fuels. The reinforcing elements used in composite materials come from plant residues to create building materials for agricultural products and construction activities and automotive industries. The development of innovative materials from food waste by researchers and industry professionals supports environmental preservation and provides functional solutions for circular economic systems (Hamid et al., 2024).

CHALLENGES IN VALORIZATION AND INDUSTRIAL APPLICATION

The commercial adoption of *B. oleracea* by-products processing needs additional work to solve multiple implementation obstacles. The main problem during extraction procedures arises from their lack of standardization (Taghian Dinani & Van Der Goot, 2023). The composition of bioactive elements found in vegetable waste depends substantially on plant species along with environmental growing conditions and harvesting stage and processing methods applied to the crops. The technical barrier exists because it is difficult to create stable extraction protocols that yield constant compound outputs. The inefficient performance of solvent-based conventional extractions contrasts with advanced microwave and ultrasound technologies that need optimization of various parameters including temperature settings and time duration plus solvent amount to reach an effective large-scale production status (Bhadange et al., 2024).

Laboratory tests must validate the *B. oleracea* waste extracts by searching for pesticide residue together with heavy metal content and microbial titter throughout the analysis. Tests for toxicological safety are mandatory to verify that compounds are safe to use by humans especially when taken orally or applied topically. The lack of standardized regulatory regulations regarding waste-derived products in numerous countries represents another obstacle that reconstructs industrial entry for product developers (Tawo & Mbamalu, 2025).

Product stability as well as the shelf-life duration of recovered compounds represents a critical matter. Phenolic compounds along with glucosinolates exhibit high sensitivity to light as well as temperature and pH conditions in the environment (Alexandre et al., 2020). The functional properties of compounds inside waste materials decrease throughout processing alongside storage activities and product formulation processes until they become ineffective for final product use. The establishment of effective stabilization and encapsulation methods requires additional processing complexity that increases product production expenses (Đorđević et al., 2015).

The industrial implementation of *B. oleracea* waste valorisation faces several barriers because of technical and economic constraints together with regulatory requirements. Empowered by interdisciplinary research, policy development and technological innovation scientists will solve the major challenges facing the complete utilization of these underutilized resources (Patra, 2023).

CONCLUSIONS

Bearing worth from *B. oleracea* by-products serves as an environmentally friendly innovative approach to managing agro-industrial waste accumulation. These vegetable waste residues contain numerous bioactive components which include glucosinolates, polyphenols, and dietary fibres that create excellent possibilities for pharmaceuticals, cosmeceuticals, nutraceuticals, biofuels, and biodegradable materials production pathways. Green extraction methods and bioconversion procedures created opportunities to produce value-added substances by processing these agricultural residues. Applications of waste *B. oleracea* towards industrial implementation require solutions to standardization problems along with scalability issues, regulatory requirements and compound stability challenges.

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