https://doi.org/10.17221/122/2025-CJFS

Recent innovations and novel technologies for the upcycling of bioactive compounds from food wastes

Aslihan Tüğen[1]*, *Özge Taştan Ülkü*[2]

[1]*Department of Food Engineering, Institute of Sciences, Afyon Kocatepe University, Afyonkarahisar, Türkiye*

[2]*Department of Food Engineering, Faculty of Engineering, Yeditepe University, İstanbul, Türkiye*

**Corresponding author: asl.tugen@gmail.com*

Citation: Tüğen A., Taştan Ülkü Ö. (2025): Recent innovations and novel technologies for the upcycling of bioactive compounds from food wastes. Czech J. Food Sci., 43: 377–397.

Abstract: This review evaluates the role of food waste reuse in sustainable food production, its associated health benefits, and technological advances in bioactive ingredient extraction. The research demonstrates that recycling bioactive food ingredients not only reduces food waste but also increases nutritional value, supports sustainability goals, and creates economic opportunities in the food industry. The process has been shown to enable the development of functional food ingredients, nutraceuticals (health-promoting food supplements), and biodegradable packaging solutions. The integration of biotechnological applications, microbial fermentation, and innovative processing methods has the potential to utilise food waste in the production of value-added products such as functional foods, biomaterials, and biofuels. The development of renewable technologies further enhances this potential. Overcoming safety risks, optimising extraction processes, and implementing global policies supporting food waste recycling are key to making sustainable solutions more effective and widespread. As new approaches emerge in research, the reuse of food waste and, therefore, achieving the zero waste goal will be facilitated by reducing the need for raw materials and increasing the added value in the food industry.

Keywords: antioxidants; bioactive components; food waste; functional ingredients; phenolic compounds

As the global population continues to grow rapidly, humanity faces the pressing challenge of fulfilling the demands of food production. However, numerous global issues, including the depletion of natural resources and the impact of climate change, contribute to significant levels of food loss and waste worldwide (Wunderlich and Martinez 2018). This phenomenon has significant economic, environmental, and social impacts on food security and human nutrition, while also leading to the loss of vital opportunities in the food value chain. To address the rapid increase in global population, it is essential to enhance food production, which will inevitably lead to a greater volume of by-products. Although international initiatives aimed at reducing food waste and attaining sustainability objectives are currently underway, there remains a necessity for further investment and research to devise and promote innovative solutions in this area (Despoudi et al. 2021).

The concept of sustainable development, which emerged to promote sustainable consumption and production, aims to ensure the effective and sustainable use of resources, thereby improving people's quality of life. Since 2000, the use of natural resources worldwide has increased from 27 billion tonnes in 1970 to 92.1 billion tonnes in 2017 (a 254% increase), and

https://doi.org/10.17221/122/2025-CJFS

continues to rise (UNEP 2019). To increase economic sustainability and reduce poverty, comprehensive development strategies that minimise negative impacts on the environment, the economy, and society must be established. The UN Sustainable Development Goal (SDG) 12.3 aims to eliminate half of the food loss at the production stage and waste at the consumption stage by 2030 through 'reduce, reuse, recycle' practices (Ardra and Barua 2022).

According to worldwide estimates, a total of 931 million tonnes of food waste is produced annually, with 569 million tonnes generated from households, 244 million tonnes from the service sector, and 118 million tonnes from the retail sector (UNEP 2022). Food waste, primarily consisting of fruits and vegetables, animal products, seafood waste, and other kitchen waste, causes environmental problems at every stage of food production. Furthermore, when disposed of in landfills and dumps, it is responsible for the release of greenhouse gases (GHG) such as carbon dioxide (CO_2) and methane (CH_4) (Sagar et al. 2018; Singh et al. 2022). Therefore, since 6.7% of all GHG emissions resulting from human activities are generated in this way, technological applications are being developed for the biological conversion of these products (De Clercq et al. 2017; Chhandama et al. 2022). In particular, it is believed that utilising food waste through low-cost and environmentally friendly methods will directly reduce the environmental burden and enable the production of biobased chemicals, materials, and energy.

By-products of food production processes, such as food waste, contain significant reserves of bioactive compounds, which are often trapped in the insoluble food matrix. This makes the use of new technologies an integral part of current research, while simultaneously rendering the application of these technologies quite challenging (Galanakis 2013). However, the current use of these food production by-products is reported to be limited due to the lack of dedicated research projects with practical applications at the industry level. Underutilisation of food by-products not only results in a severe loss of valuable resources but also causes environmental problems by increasing environmental pollution burdens (greenhouse gas emissions and landfill burden etc.) (Gómez-García et al. 2021). This problem requires research efforts to find suitable upcycling strategies for these by-products.

Food waste is a significant global challenge, characterised by its diversity in composition and the complexities inherent in its management. The nature of food waste varies considerably across different regions and cultures, influenced by consumer behaviour, local agricultural practices, and waste management systems. Importantly, real food waste streams are typically complex mixtures of proteins, polysaccharides, fats, and micronutrients, often contaminated with extraneous matter. Thus, modern separation methods must be evaluated not only in simplified laboratory models but also in terms of their practical applicability to such heterogeneous, real-world food waste compositions (Parra-Pacheco et al. 2024).

The majority of by-products from food production processes are solid and insoluble, comprising lignin, hemicellulose, and cellulose in varying proportions (Figure 1). These polymers have a matrix structure in which various valuable components, such as phenolic compounds (PC), are present in different forms. Furthermore, plant cells also contain molecules important for their technological functionality or health effects, such as lipids, carotenoids, and xanthophylls. However, these compounds are also bound or trapped in insoluble materials. Therefore, one of the most common methods for upcycling food production by-products is to extract these beneficial components by breaking down the plant cell wall structure. In this context, the upcycling of fruit and vegetable by-products has been reported as a successfully applied approach that aims to prevent food by-products from exiting the food supply chain by converting them into valuable components (Thorsen et al. 2022, 2024).

In addition, bioactive compounds (BCs) are natural or synthetic compounds that exhibit biological activity in living tissues, producing various effects, including antioxidant, antimicrobial, anti-inflammatory, and prebiotic properties. They are generally classified according to their physicochemical properties, distribution in nature, biosynthetic pathways or biological and pharmacological effects (Leichtweis et al. 2021). This classification is associated with a diverse range of chemical compounds commonly found in foods, including phenolic compounds, carotenoids, alkaloids, vitamins, dietary fibres, fatty acids, volatile compounds, anthocyanins, and other pigments (Leichtweis et al. 2021; Vilas-Boas et al. 2021; Figure 2).

The primary sources of foodborne BCs are fruits, vegetables, legumes, whole grains, nuts, seeds, mushrooms, herbs, and spices (Martillanes et al. 2020), as well as animal-derived components such as protein, enzymes, polyunsaturated fatty acids (PUFAs), vitamins, and biopolymers (Zhang et al. 2015). BCs are commonly found in foods, as well as in underutilised sources, such as food production by-products. Due to improper management

https://doi.org/10.17221/122/2025-CJFS

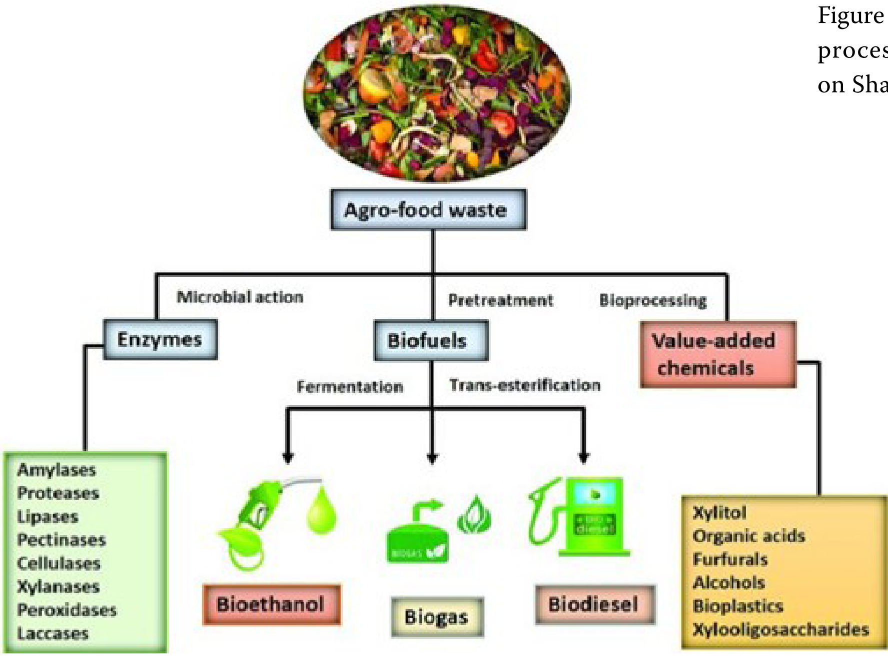

Figure 1. By-products of food production processes, such as food waste (based on Sharma et al. 2022)

of production processes, valuable by-products are lost, and these by-products have negative impacts on the environment. Indeed, the Food and Agriculture Organisation (FAO) has reported that fruit and vegetable losses account for up to 60% of total horticultural production, and estimated that 25–30% of food by-products are generated as a result of fruit processing operations (Sagar et al. 2018). In this context, many institutions and organisations are turning towards promoting the adequate reuse of valuable by-products from food (seeds, peels, pulps, skins etc.) and their integration into the circular economy scheme as concrete renewable candidates for sustainable 'zero policy' practices (EEA 2023).

The recovery of bioactive components from non-edible biological residues and by-products has been reported to provide additional economic value when used as new raw materials in production processes (Grimaldi et al. 2022). Different extraction methods have been reported for the efficient recovery of BCs from such residues. In recent years, green extraction methods such as ultrasound-assisted, microwave-assisted, enzyme-assisted, and supercritical fluid extraction have

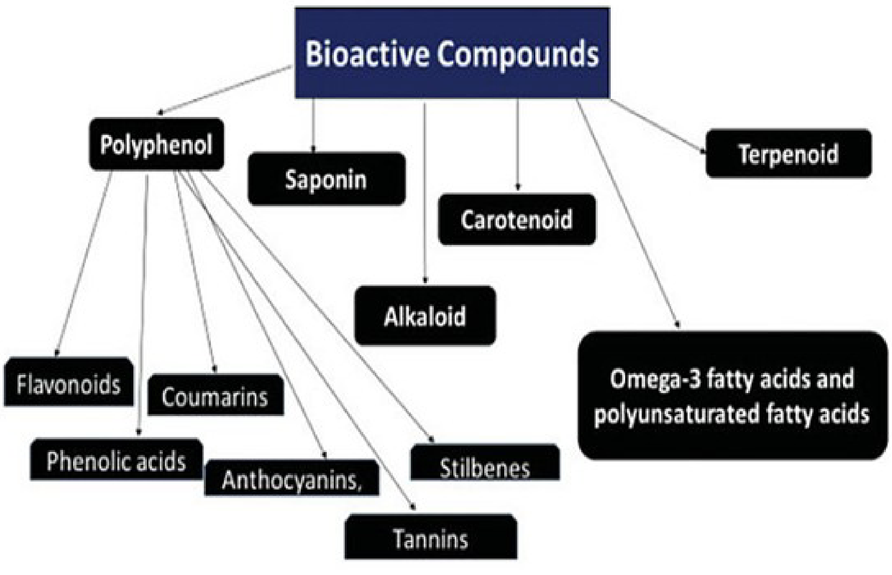

Figure 2. Functional bioactive components/compounds (based on Adefegha 2018)

https://doi.org/10.17221/122/2025-CJFS

replaced traditional methods (maceration, infusion, Soxhlet extraction), which are expensive, time-consuming and require large amounts of organic solvents (Panzella et al. 2020). Natural BCs, such as sugars and antioxidants, have been reported to have nutritional and therapeutic potential value, as well as importance in terms of reliability and profitability. On the other hand, the application of BCs from by-products in packaging as eco-additives, such as fillers, plasticisers, dyes, antioxidants, and compatibilizers, to improve the functional and structural properties of a wide range of biomaterials is mentioned as an alternative method for the technological upcycling of by-product raw materials. In addition, sustainable methodologies focusing on sustainable extraction approaches of natural BCs and their use as natural additives and preservatives in the food industry have also been described (Faustino et al. 2019; Socas-Rodríguez et al. 2021; Vilas-Boas et al. 2021). Applications of these ingredients in pharmaceuticals and cosmetics have been addressed (Simitzis 2018; Laura et al. 2021), while some studies have also evaluated the design of innovative eco-friendly materials (edible films, coatings and biocomposites) by recycling materials recovered from food by-products (Díaz-Montes and Castro-Muñoz 2021; Das et al. 2022; Sani et al. 2023).

The extraction of bioactive substances from food waste requires a multifaceted approach that involves effective pre-treatments, optimised extraction methodologies, and consistent strategies to manage biological contamination. Because food waste sorting is inefficient, a high level of contaminants accumulates and requires more complex downstream treatment. Therefore, pretreatment is crucial in food waste (FW) management. Pretreatment methods vary and include physical processes (such as crushing and drying), biological techniques (like enzymatic treatments), and chemical methods (for example, acid or alkaline reagents). Biological treatment methods provide an eco-friendly, sustainable response to the growing food waste problem by using microorganisms to decompose organic waste into useful products like biogas, fertilisers, and other materials. Popular for their efficiency and low environmental impact, these processes can operate under aerobic (oxygen-present) or anaerobic (oxygen-absent) conditions, reducing greenhouse gas emissions while producing resources for energy and soil enhancement (Xiao et al. 2024).

Research on methods developed to recycle food industry wastes, such as phenolic compounds, antioxidants, polyphenols, and probiotics, are generally driven by concerns about the environmental, economic, and social problems created by food waste. It is stated that the waste of one-third of food produced and the underutilisation of waste result in resource inefficiency and economic losses (Nirmal et al. 2023; Nutrizio et al. 2024). In recent years, the field has shifted from traditional extraction methods based on organic solvents and energy-intensive processes to biotechnological approaches, including non-thermal extractions, supercritical fluid extraction, and enzymatic and fermentation-assisted extractions, which have become the most effective methods for addressing this inefficiency (Fierascu et al. 2021; Herzyk et al. 2024; Nutrizio et al. 2024). Indeed, these methods offer significant contributions to achieving sustainability goals by transforming agro-industrial by-products into high-value, functional ingredients (Mavai et al. 2025). In practice, fortification of food ingredients, preservation, and health-promoting applications produce bioactive compounds of high economic value and application while reducing environmental damage (Veneziani et al. 2017; Enciso-Martínez et al. 2024). However, while most published studies test extraction and recovery strategies on relatively homogeneous waste fractions (e.g. fruit peels or pulp), comprehensive evaluations of methods applicable to heterogeneous waste streams are still limited. Addressing this gap requires the development of sustainable extraction technologies (Bekavac et al. 2025).

Despite progress, the efficient recovery and upcycling of bioactive compounds from diverse food industry wastes remain challenging. Conventional extraction techniques often involve high solvent consumption, long processing times, and potential degradation of sensitive compounds, limiting their scalability and environmental compatibility (Chang et al. 2022; Ebrahimi and Lante 2022). Emerging green technologies, while promising, face limitations related to cost, process optimisation, and integration into industrial settings (Vilas-Franquesa et al. 2024; Zheng et al. 2025). Moreover, the synergistic use of probiotics in enhancing the bioactivity and stability of phenolic compounds introduces additional complexity and requires further exploration (Moussaoui et al. 2021; Wang et al. 2024). A notable gap exists in comprehensive evaluations that integrate advanced extraction methods with probiotic biotransformation to maximise yield, bioactivity, and sustainability (Martí-Quijal et al. 2021; Ahmad et al. 2024; Gong et al. 2024).

The purpose of this systematic review is to critically assess and synthesise current technological methods for upcycling phenolic compounds, antioxidants, polyphenols, and probiotics from the food industry by-products. This review aims to bridge the identified

https://doi.org/10.17221/122/2025-CJFS

knowledge gap by evaluating the efficacy, sustainability, and industrial applicability of emerging extraction and bioprocessing techniques. Considering the existing research in the literature, this discussion examines the application areas, challenges, and future research directions of upcycling methods.

MATERIAL AND METHODS

Material. This research investigates the potential of bioactive food ingredients for repurposing and their applications in the food industry. A systematic literature search was conducted in accordance with PRISMA guidelines to ensure transparency and reproducibility. The study material was sourced from Google Scholar, Web of Science, Scopus, Elsevier, and SpringerLink databases. The study evaluated peer-reviewed articles in English published between 2000 and 2025, a period when research on sustainable extraction methods and circular economy applications was on the rise. Conference proceedings, theses, reports, and non-peer-reviewed documents were excluded.

Research design. The literature review was conducted by evaluating sources that provide comprehensive information on the benefits, technological developments, and challenges associated with repurposing bioactive ingredients. In the literature search using Boolean operators, keywords such as 'recycling' AND 'food industry', 'bioactive compounds' AND 'food waste' OR 'by-products', 'circular economy' AND 'food sector', 'phenolic compounds' OR 'antioxidants' OR 'polyphenols' AND 'valorisation' and 'probiotics' AND 'food by-products' were used.

Data sources. The collected materials were categorised based on the methods used, bioactive ingredients analysed, and potential applications in the food industry. The classification process was carried out through a structured document analysis to provide a systematic evaluation of the available literature. The classification and evaluation of the findings are presented in Table 1, reflecting the main themes and trends in the reuse of bioactive food ingredients.

Research focus. This review aims to evaluate the use of bioactive food ingredients in raw material processes that increase the value of food waste by examining the reuse of bioactive food ingredients. Innovative extraction techniques and integrated biotechnological processes for the reuse of food waste are examined from a sustainability perspective. Various approaches, including enzymatic hydrolysis, fermentation, and green chemistry applications, are discussed to optimise the recovery of bioactive ingredients. The research also examines the impact of these recycling techniques on food safety, nutritional quality, and economic viability.

Data analysis. A systematic literature review was applied in this research using the PRISMA methodology. In the first stage, 107 documents were obtained, and after removing duplicate records, 78 documents were evaluated. In the eligibility stage, 56 full-text articles were examined, and 22 were excluded from the study because they were irrelevant, contained outdated criteria or did not contain empirical findings (Figure 3).

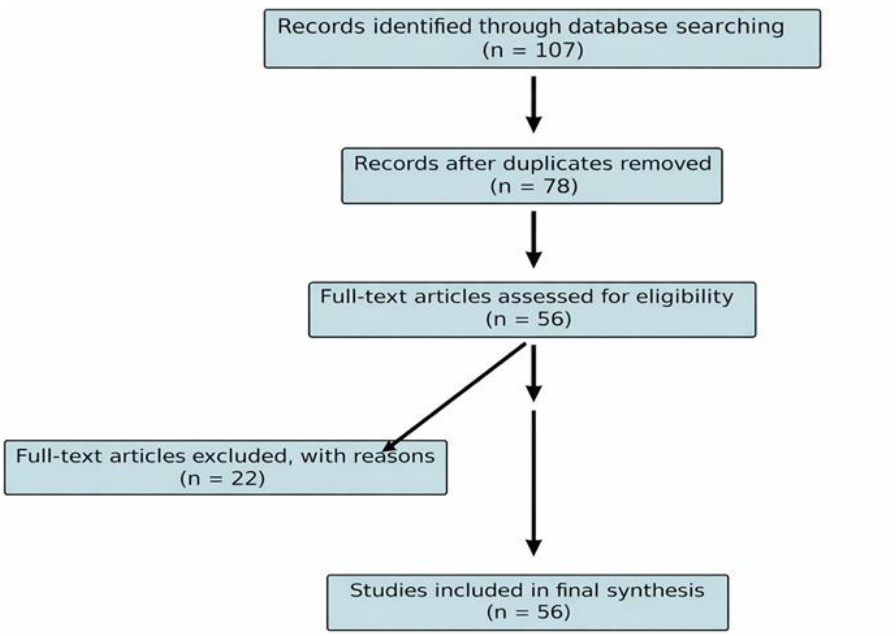

Figure 3. PRISMA diagram

https://doi.org/10.17221/122/2025-CJFS

Table 1. References materials

Category	Aim	Method	Results	Reference
Upcycling of food waste and by-products	to examine non-thermal green extraction techniques and life cycle assessment in the upcycling of food waste and by-products	non-thermal extraction techniques (such as microwave-assisted and ultrasound-assisted extraction), and life cycle assessment	non-thermal techniques enable the efficient extraction of bioactive compounds from food waste, showing promise for sustainable upcycling	Nutrizio et al. (2024)
	to investigate the extraction techniques and bioactive properties of polysaccharides, proteins, carotenoids, and fatty acids from shrimp waste	chemical extraction, microbial fermentation, enzyme-assisted extraction, and microwave and ultrasound-assisted extraction	extracted compounds from shrimp waste exhibit antioxidant, antimicrobial, anti-inflammatory, and antitumour properties	Rossi et al. (2024)
	to study the lipopigment production potential from food waste streams using bacterial fermentation	bacterial fermentation using *Pseudomonas aeruginosa* for phenazine-based lipopigment production	stale bread waste supports bacterial lipopigment production, which exhibits antimicrobial and anticancer properties	Pantelic et al. (2024)
	use microbial biocatalysis to convert food waste into biofuels, bioplastics, and other valuable products	microbial biocatalysis to produce biofuels, bioplastics, and nutraceuticals	microbial biocatalysis enables the conversion of food waste into biofuels and bioplastics, supporting a sustainable economy	Patel et al. (2024)
	to develop medical products by extracting bioactive compounds from food waste	extracting bioactive compounds from food waste and using them in medical applications	food waste contains essential raw materials for the production of biomaterials	Mahabeer and Jin (2024)
Upcycling in the food industry and supply	to evaluate the nutritional and antioxidant potential of brewing by-products such as spent grains and hops	chemical characterisation, antioxidant assays (FRAP, DPPH, ABTS), and phenolic compound quantification	brewing by-products contain high levels of protein, fibre, and polyphenols, making them valuable for upcycling and reuse	Bravi et al. (2021)
	to analyse the emerging and existing recycling technologies in the food industry	reviewing upcycling technologies in the food industry and existing challenges	new technologies and regulatory frameworks are needed for efficient food waste upcycling	Idrishi et al. (2022)
	to review sustainable strategies for transforming plant-derived food waste into bioactive ingredients	comprehensive literature review of bioactive compound recovery from food waste	industrial food waste contains bioactive compounds suitable for nutraceutical and cosmetic applications	Jaouhari et al. (2023)
	to explore sustainable opportunities for cereal by-products to enhance human and animal nutrition	circular economy principles applied to cereal by-products for sustainable food production	cereal by-products have significant nutritional potential for human and animal consumption	Nahi and Siankevich (2023)
	to explore strategies for reducing food waste in restaurants and catering through upcycling	assessment of food waste generation in restaurants, review of waste prevention strategies, and evaluation of consumer attitudes toward waste reduction	food waste in restaurants can be reduced by up to 40% through the implementation of improved waste management strategies and technological innovations	Kanwal et al. (2024)
	to investigate the upcycling potential of distiller's grains and other cereal by-products for food applications	reviewing the existing and future approaches for cereal by-product upcycling	distiller's grains and cereal by-products can be fully utilised through targeted upcycling strategies	Roth et al. (2024)

https://doi.org/10.17221/122/2025-CJFS

Table 1 to be continued

Category	Aim	Method	Results	Reference
Upcycling in the food industry and supply	to optimise the extraction of cyanidin-rich antioxidants from red araçá fruit waste and evaluate their food applications	microwave-assisted extraction for optimal pigment recovery and stability testing in yoghurt applications	cyanidin-rich pigments extracted from araçá fruit waste show vigorous antioxidant activity and enhance food stability and sensory appeal	Caicedo-Paz et al. (2024)
	to analyse the effects of different drying techniques on the nutritional and health properties of brewers' spent grain for food upcycling	comparison of the effects of infrared and hot-air drying on the composition and health benefits of brewers' spent grain, including animal trials	the infrared and hot-air drying of brewers' spent grain affects its fibre content, phenolic compounds, and potential health benefits	Thai et al. (2024)
Bioprocessing and biotechnology for upcycling	to extract high-value chitin and chitosan from seafood processing waste using biological fermentation	biological fermentation of seafood processing waste to extract chitin and chitosan for sustainable applications	biological fermentation efficiently extracts chitin and chitosan from seafood waste, offering sustainable solutions for the food and biomedical industries	Tan (2021)
	to convert lignocellulose into bacterial nanocellulose and enrich it with black raspberry extract for its functional properties	enzymatic hydrolysis of wood waste to produce bacterial nanocellulose, followed by functionalisation with the antioxidant-rich black raspberry extract	upcycling lignocellulose into bacterial nanocellulose provides a sustainable material with potential applications in food and medicine	Ponjavic et al. (2023)
	to enhance the nutritional value of agro-industrial by-products through bioprocessing for animal feed applications	use of fungi, yeast, bacteria, and enzymes to improve the protein content and digestibility of agro-industrial by-products	bioprocessing can enhance protein quality, improve fibre digestibility, and detoxify agro-industrial by-products, making them viable for animal feed	Sun et al. (2024)
	to develop a guidance tool (food by-products bioprocess wheel) for industry professionals to use food waste efficiently	development of a guidance tool to assist the industry in selecting biotechnological upcycling approaches	the food by-products bioprocess wheel helps industry professionals optimise food waste upcycling	Vilas-Franquesa et al. (2024)
	to analyse the potential of using food industry waste in Spirulina cultivation for sustainable protein production	evaluation of Spirulina cultivation using food industry waste as a nutrient source	upcycling food industry waste in Spirulina cultivation supports Sustainable Development Goal 12 and reduces the carbon footprint associated with this process	Thevarajah et al. (2024)
	to explore microalgal-based biorefinery solutions for using food waste as a nutrient source	analysis of microalgal cultivation using food waste streams and biorefinery feasibility assessment	microalgal cultivation using food waste contributes to sustainable biorefinery solutions	Wang et al. (2024)
	to extract and evaluate nanocellulose from food by-products for various applications in food and packaging	extraction and structural characterisation of nanocellulose from food waste for use in food and packaging applications	nanocellulose derived from food waste has promising applications in food, biomedicine, and sustainable packaging	Kim and Doh (2024)

https://doi.org/10.17221/122/2025-CJFS

Table 1 to be continued

Category	Aim	Method	Results	Reference
Upcycling for nutraceuticals, pharmaceuticals, and medical applications	to extract bioactive compounds and fibre concentrates from the quince peel using multicomponent extraction techniques	multicomponent extraction methods for valorising by-products	quince peel extracts exhibit antioxidant and antimicrobial properties	Pereira et al. (2023)
	to explore innovative strategies for transforming agricultural residues into pharmaceutical compounds	enzymatic hydrolysis, green solvents, microwave processing, ultrasonic processing, ozonolysis, and organosol processes	upcycling agricultural residues contributes to environmental sustainability and advances in pharmaceutical development	Bejenaru et al. (2024)
	to evaluate fruit-vegetable waste for bioactive compounds and its contribution to the circular economy	microwave, ultrasound, supercritical fluid, and enzyme-assisted extraction methods	fruit and vegetable waste have potential applications in the functional food and pharmaceutical industries	Noor et al. (2024)
	to develop an improved pH-driven method for upcycling polyphenols from food by-products	optimisation of pH-sensitive polyphenol extraction and encapsulation in nanoemulsions	the improved pH-driven method enhances the stability and antioxidant activity of polyphenols, making the food waste-derived extracts more viable for food fortification	Gong et al. (2024)
	to extract bioactive peptides from the tuna fishery by-products using enzymatic hydrolysis	enzymatic-assisted hydrolysis of the tuna mixed biomass and characterisation of bioactive peptide fractions	the tuna protein hydrolysates exhibited strong antioxidant properties, offering potential for nutraceutical applications	Grasso et al. (2024)
	to enhance the polyphenol recovery from mango peels through sequential enzymatic and fermentation processing	sequential enzymatic hydrolysis and bacterial fermentation of mango peels for functional ingredient production	mango peel fermentation significantly increased the availability of bioactive aglycones, enhancing their functional properties	Vilas-Franquesa et al. (2024)
Consumer behaviour, regulations, and sustainability aspects	to analyse consumer preferences and perceptions regarding upcycled food ingredients	survey-based study analysing millennial consumers' acceptance of upcycled food products	consumers willing to buy upcycled foods were more likely to value sustainability and read ingredient labels	Coderoni and Perito (2021)
	to discuss the role of upcycled foods in addressing global nutrition challenges and sustainability	review of upcycled food trends and their nutritional contributions	upcycled foods contribute to global sustainability, but they require a greater emphasis on nutrition to align with dietary guidelines	Thorsen et al. (2022)
	to highlight the importance of bioactive compounds in sustainable nutrition and health systems	review of bioactive food compounds about nutrition, sustainability, and planetary health	bioactive compounds from food waste can support nutrition, sustainability, and circular economy initiatives	Kussmann et al. (2024)
	to examine the regulations, limitations, and prospects of food upcycling in South Korea	review of food loss statistics, regulatory frameworks, and environmental assessment requirements	regulatory requirements and microbiological safety concerns limit food upcycling in South Korea, but it has significant growth potential	Kim (2024)

https://doi.org/10.17221/122/2025-CJFS

Table 1 to be continued

Category	Aim	Method	Results	Reference
... Consumer behaviour, regulations, and sustainability aspects	to analyse consumer motivations and behaviours toward upcycled food from a sustainability perspective	survey-based study using the Value-Attitude-Behaviour (VAB) model to assess consumer perspectives	health values significantly impact consumer willingness to adopt upcycled food, whereas perceived novelty and environmental benefits have a lesser influence	Huang et al. (2024)
	to evaluate bioactive compounds from food waste and their applications in the food and health industries	comprehensive study of the extraction techniques, bioactive compound recovery, and applications	food waste contains bioactive compounds that are beneficial for health, but consumer awareness remains a barrier to their widespread application	Negi et al. (2025)
Technological advances and novel approaches in upcycling	to evaluate the antioxidant potential of high-pressure homogenised suspensions from vegetable peels	processing of potato and carrot peels using high-speed stirring and high-pressure homogenisation, followed by antioxidant analysis	the high-pressure homogenised suspensions showed more potent antioxidant activity compared to the bulk suspensions	Yassin et al. (2021)
	to evaluate the incorporation of brewers' spent grain into shortbread formulations for functional food applications	partial substitution of wheat flour with brewers' spent grain and oat flakes, followed by nutritional and sensory evaluation	shortbreads with upcycled brewers' spent grain meet fibre health claims, maintain acceptable sensory properties, and do not increase the sugar or fat content	Sileoni et al. (2022)
	to assess pear pomace as a sustainable food ingredient, alone and in combination with yeast protein extract	chemical composition analysis, rheology testing, and microstructural characterisation of the pear pomace formulations	pear pomace exhibited high fibre and phenolic content, while the yeast protein extract enhanced its protein value	Fernandes et al. (2022)
	to evaluate technological and biotechnological strategies for reusing agro-food by-products in high-value food production	review of biotechnological and fermentation techniques for transforming agro-food waste into high-value functional ingredients	agro-food by-products contain functional bioactive compounds that can be used in food production, thereby reducing waste and supporting sustainability	Difonzo et al. (2022)
	to explore strategies for converting food waste into economically valuable products	converting food waste into novel foods, animal feed, and bioenergy; regulatory frameworks	upcycling food waste reduces greenhouse gas emissions and enhances food security	Bangar et al. (2024)
	to assess the impact of processing and storage on the properties of vegetable waste powders	processing vegetable waste through dehydration, milling, and testing the physicochemical, antioxidant, and storage stability properties	hot-air drying at 7 0 °C improved the antioxidant properties, while the freeze-dried powders exhibited better water retention, storage reduced the antioxidant activity	Bas-Bellver et al. (2023)
	to review the bioactive compounds from fruit and vegetable waste and their value-added potential in food products	literature review of bioactive compounds (antioxidants, antimicrobials, natural colourants) in the fruit and vegetable industry waste	fruit and vegetable waste contains bioactive compounds suitable for food preservation, colouring, and antimicrobial applications	Aqilah et al. 2023
	to explore how spectroscopy and chemometrics enable the upcycling of raw materials from meat and fish production	analysis of enzymatic protein hydrolysis and chemometric modelling for characterising protein quality in the remaining raw materials	spectroscopy and chemometrics can optimise the upcycling of fish and poultry by-products, but challenges exist in industrial scaling	Måge et al. (2023)

https://doi.org/10.17221/122/2025-CJFS

Table 1 to be continued

Category	Aim	Method	Results	Reference
	to assess the dry fractionation of purple bread wheat side streams to enhance the bioactive compounds and reduce the harmful elements	microstructure analysis, antioxidant activity assessment, and fractionation techniques	dry fractionation enhances the antioxidant content of purple bread wheat while reducing the amount of harmful elements	Jiang et al. (2024)
	to examine pretreatment methods for food waste to improve the upcycling efficiency	life cycle assessment and innovative pretreatment strategies for food waste bioconversion	pretreatment methods enhance the efficiency of food waste upcycling for various industries	Sagar et al. (2024)
	to explore how spectroscopy and chemometrics enable the upcycling of raw materials from meat and fish production	analysis of enzymatic protein hydrolysis and chemometric modelling for characterising protein quality in the remaining raw materials	spectroscopy and chemometrics can optimise the upcycling of fish and poultry by-products, but challenges exist in industrial scaling	Måge et al. (2023)
	to assess the dry fractionation of purple bread wheat side streams to enhance the bioactive compounds and reduce the harmful elements	microstructure analysis, antioxidant activity assessment, and fractionation techniques	dry fractionation enhances the antioxidant content of purple bread wheat while reducing the amount of harmful elements	Jiang et al. (2024)
Technological advances and novel approaches in upcycling	to examine pretreatment methods for food waste to improve the upcycling efficiency	life cycle assessment and innovative pretreatment strategies for food waste bioconversion	pretreatment methods enhance the efficiency of food waste upcycling for various industries	Sagar et al. (2024)
	to assess the potential of microalgal cultivation for nutrient recovery from food waste	hydrolysis strategies, metabolic analysis, and economic/environmental impact assessments	microalgae cultivation offers a sustainable method for recovering nutrients from food waste, but it faces challenges in terms of economic feasibility and consumer acceptance	Ramandani et al. (2024)
	to provide an overview of biotransformation technologies for upcycling food waste	biochemical and microbial biotransformation approaches for valorising food waste	biotransformation technologies enable the conversion of food waste into bio-based ingredients, reducing the reliance on synthetic food additives	Pinela et al. (2024)
	to assess the nutritional and functional properties of melon seed oil processing by-products for food applications	chemical and nutritional analysis of defatted melon seeds and comparison with other seed by-products	defatted melon seed oil processing by-products are rich in protein, dietary fibre, and antioxidants, making them valuable for food reformulation	Zhang et al. (2024)
	to explore the applications of innovative alginate nanomaterials in food delivery, preservation, packaging, and waste upcycling	development of pH-sensitive and stimuli-responsive alginate-based nanomaterials for sustainable food applications	smart alginate nanomaterials provide innovative solutions for food preservation and waste upcycling	Rathee et al. (2024)
	to investigate fungal fermentation in traditional foods as a method for upcycling agricultural by-products	multi-omics analysis of fungal fermentation in traditional food systems for waste-to-food transformation	fungal fermentation can efficiently convert food by-products into edible and nutritious products, offering a sustainable approach to food upcycling	Rekdal et al. (2024)

https://doi.org/10.17221/122/2025-CJFS

Table 1 to be continued

Category	Aim	Method	Results	Reference
Technological advances and novel approaches in upcycling	to analyse the effect of particle size on phenolic bioaccessibility in upcycled fruit pomace	drying and grinding of the fruit pomace, in vitro digestion, antioxidant assays, and structural analysis using FESEM	grape pomace had the highest antioxidant capacity, while apple pomace benefited most from grinding at 1 mm	Arcia et al. (2024)
	to develop rice bran-based emulsifiers for improving the texture and stability of rice crackers	development and optimisation of rice bran-derived emulsifiers for rice snack production	rice bran-based emulsifiers enhanced the texture and stability of rice crackers, thereby reducing food industry waste	Park et al. (2024)
	to utilise the grape juice non-pomace residue for creating biodegradable freshness indicators	polyelectrolyte complexation of grape juice residue to develop food freshness indicators	the grape juice non-pomace residue provided stable biodegradable freshness indicators for food packaging	Azevedo and Noreña (2024)
	to examine the potential of food waste-derived feedstocks for the microbial fermentation of polyhydroxyalkanoates (PHAs)	microbial fermentation of food waste feedstocks for PHA production	PHAs derived from food waste can be used to produce biodegradable plastics, thereby reducing reliance on petroleum-based materials	Bhatia et al. (2024)
	to explore novel deep eutectic solvents for extracting bioactive compounds from coffee waste	extraction of bioactive compounds from spent coffee grounds using natural deep eutectic solvents (NADES)	NADES were found to be effective in extracting bioactive compounds from coffee waste for use in cosmetics	Costa et al. (2025)
	to study the interaction of phenolic-rich extracts with glucose metabolism for developing hypoglycaemic food products	green extraction techniques to study phenolic compound-glucose interactions	phenolic-rich extracts from food waste can reduce the free glucose content and inhibit the activity of digestive enzymes	Costa et al. (2025)
	repurpose fruit processing by-products into flour with improved nutritional properties for food applications	characterisation of fruit by-product flours from common fruits and evaluation of their nutritional, sensory, and functional properties	fruit by-product flours enhance the nutritional profile of white flour but may affect sensory properties at higher substitution levels	Benvenutti et al. (2025)

FRAP – fluorescence recovery after photobleaching; DPPH – 2,2-diphenyl-1-picrylhydrazyl; ABTS – 2,2'-azino-bis(3-ethylbenzothiazoline-6-sulfonic acid); FESEM – field emission scanning electron microscopy

As a result, 56 articles focusing on the recovery of bioactive ingredients through reuse were categorised, and the findings were presented in the findings and discussion section.

RESULTS

In today's world, the increasing concern for food waste and sustainability has made it essential to reevaluate agricultural and food by-products and extract their functional components. The studies presented in the literature aim to address the challenge of recovering biologically active components and integrating them into the pharmaceutical, nutraceutical, and food industries through various extraction and transformation methods. It is stated that evaluating food waste and by-products provides benefits in terms of nutritional value, environmental impact, and economic sustainability of different upcycling methods.

For the food industry, the transformation of waste into alternative products through reuse is considered important for the protection of raw material resources,

https://doi.org/10.17221/122/2025-CJFS

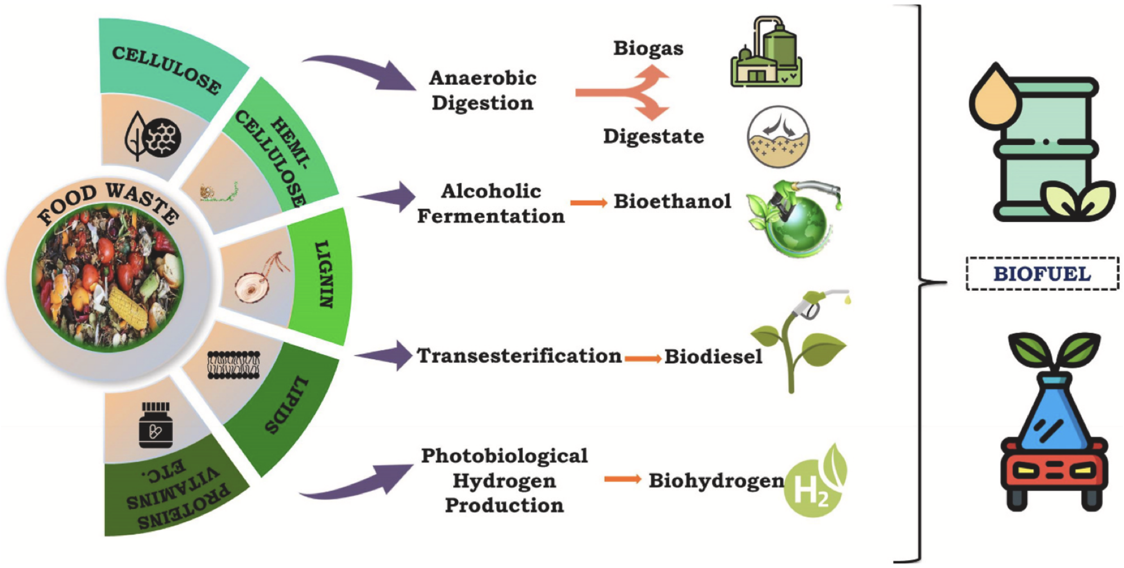

Figure 4. Food waste upcycling process (based on Bangar et al. 2024)

the reduction of environmental waste, and the creation of economic added value (Figure 4). Nutrizio et al. (2024) reported that the sustainable evaluation of food waste and by-products will be possible, especially with non-thermal extraction techniques. It has been revealed that non-thermal techniques, such as ultrasonic, microwave, and enzyme-based processes, facilitate the extraction of biologically active components from food waste and support the recovery of valuable health-promoting proteins and phenolic compounds from food waste, which can be obtained efficiently and yield positive results in terms of environmental impacts (Nutrizio et al. 2024). However, these methods are mostly applied under laboratory conditions with relatively uniform waste, and their adaptation to complex waste mixtures still requires empirical validation (Bekavac et al. 2025).

Rossi et al. (2024) investigated the extraction techniques for polysaccharides, proteins, carotenoids, and fatty acids from shrimp waste. They determined that the components obtained by methods such as chemical extraction, microbial fermentation, and enzyme-assisted extraction exhibited antioxidant, antimicrobial, anti-inflammatory, and antitumor properties. Therefore, it was stated that seafood waste can be used in the functional food and pharmaceutical industries. In addition, biopigment production from food waste is also considered important in terms of reuse as a key recycling strategy. Pantelic et al. (2024) produced phenazine-based biopigments with the microbial fermentation process using *Pseudomonas aeruginosa*. According to research, biopigments have been found to possess antimicrobial and anticancer properties. The utilisation of food waste in biotechnological applications is beneficial in terms of health, the environment, and the economy.

Ran et al. (2019) highlighted that plant by-products contain a large percentage of high-value functional substances, such as antioxidants, pectin, and polyphenols. Recently, many research studies have concentrated on innovative technologies that promise to overcome issues such as time consumption, inefficiency, and low yield, among others, which exist in most conventional techniques. Consequently, to achieve the recovery of nutraceuticals from high-added-value by-products, it is necessary to have more knowledge of these novel technologies and, more importantly, explore the possibility of applying these latest technologies to the downstream recovery processing.

Sommer et al. (2023) developed a sustainable method for upcycling black currant pomace into a highly palatable fermented beverage using the fungus *Wolfiporia cocos*. As *W. cocos* is an edible medicinal fungus, the beverage has potential not only as a biocatalyst for flavour and fruit acid formation but also as a functional drink. It was concluded that fermenting black currant pomace with *W. cocos* offers a promising, sustainable, and scalable approach to create a pleasant-tasting functional beverage, highlighting the potential for further investigation into its health benefits.

https://doi.org/10.17221/122/2025-CJFS

Low and Chong (2024) investigated the extraction methods for bioactive compounds, including dietary fibre, phenolic compounds, seed oil, natural colourants, and enzymes, from passion fruit wastes. Green extraction techniques are suggested for extracting bioactive compounds from passion fruit wastes due to their high yield, energy efficiency, and environmental friendliness. Additionally, the extracted bioactive compounds have the potential to serve as raw ingredients, food additives, and food packaging materials in the food industry.

Pereira et al. (2023) studied the total upcycling of quince (*Cydonia oblonga* Mill.) peel into bioactive extracts (BEs) and fibre concentrates (FCs). The multicomponent extraction processes were optimised using response surface methodology (RSM) coupled with a 20-run experimental design, where the effects of time (1–120 min), temperature (25–95 °C), and EtOH percentage (0–100%) were combined. In addition to the extraction yields, BEs were analysed for phenolic compounds, organic acids, and other water-soluble constituents, while FCs were characterised for their colour and dietary fibre content. Statistically valid theoretical models were obtained by fitting these dependent variables to a quadratic equation and used to predict optimal extraction conditions. Those obtained for phenolic compounds and malic acid were experimentally validated, yielding 9.3 $mg \cdot g^{-1}$ and 7.6 $g \cdot (100\ g)^{-1}$ of these bioactive constituents, respectively, and about 51% (w/w) FC.

Imeneo et al. (2023) investigated the effect of adding natural antioxidants recovered from 'Rossa di Tropea' onion waste to maintain or improve the functional and qualitative characteristics of white bread. The total phenolic content, antioxidant activity, and sensorial aspects of the different enriched samples were studied during the storage period. The 'Rossa di Tropea' onion skins proved to be a good source of natural polyphenols, and their use in white bread production has resulted in a significant increase in bioactive compound content and antioxidant activity [ABTS (2,2'-azino-bis(3-ethylbenzothiazoline-6-sulfonic acid)) and DPPH (2,2-diphenyl-1-picrylhydrazyl) assays]. Moreover, the enriched bread exhibited acceptable quality attributes in terms of odour, colour, and taste, despite an increase in firmness during storage compared to the control sample. The obtained results suggest the possibility of applying the antioxidants recovered by 'Rossa di Tropea' onion waste as ingredients in the formulation of bakery products to obtain new food with functional characteristics.

Mahabeer and Jin (2024) stated that bioactive components obtained from food waste can be utilised in the production of biomaterials. In addition, Patel et al. (2024) demonstrated that biofuels, bioplastics, and nutraceutical products can be produced from food waste using microbial biocatalysis processes, and that utilising it as a raw material for energy and material production has benefits. When the studies conducted were evaluated, it was observed that food waste can provide valuable raw materials for medical applications and that this approach offers both economic and environmental advantages, with significant economic value. Therefore, it was determined that reuse with different extraction, transformation techniques, and biotechnological applications will create significant opportunities in terms of sustainable production and waste management strategies.

The potential for upcycling in the food industry is a highly significant factor in achieving sustainability goals, particularly in terms of enhancing nutritional value and reducing waste. However, studies have shown that new technologies, regulatory policies, and awareness-raising activities are necessary to make this process more effective. For example, a study conducted in the beer industry found that spent grains and hops, by-products, have high protein, fibre, and polyphenol content, and therefore should be evaluated (Bravi et al. 2021). Similarly, Thai et al. (2024) investigated the impact of various drying techniques on the nutritional content and health benefits of spent beer grains, finding that these grains possess high upcycling potential. Idrishi et al. (2022) stated that there is a need for innovations and regulatory frameworks in existing and emerging recycling technologies applied in the food industry. In this context, Kanwal et al. (2024) stated that effective waste management and technological innovations can reduce food waste by 40% in strategies aimed at reducing food waste in restaurants and catering services. Jaouhari et al. (2023) reported that industrial food waste contains bioactive compounds that can be utilised in the nutraceutical and cosmetic industries. Indeed, Caicedo-Paz et al. (2024) reported that the components could increase the stability and sensory quality of foods, such as yoghurt, by optimising the extraction of antioxidant pigments, mainly cyanidin, from red araçá fruit waste. Nahi and Siankevich (2023) reported that cereal by-products have great nutritional potential for human and animal nutrition. Roth et al. (2024) further reported that all distillers' grains and other cereal by-products can be fully evaluated using upcycling strategies in line with specific targets, and

https://doi.org/10.17221/122/2025-CJFS

that the zero-waste concept can be implemented. As a result, the potential for upcycling in the food industry seems to have serious potential in the context of sustainability goals. Nevertheless, limitations in assessing industrial wastes, despite the R&D and laboratory studies, highlight the need for further practical studies and mandatory holistic frameworks.

Tan (2021) showed that chitin and chitosan can be obtained from seafood processing waste through biological fermentation. It has been stated that these bioactive polymers have various applications in the food and biomedical industries, supporting bioprocess approaches. Ponjavic et al. (2023) investigated the conversion of wood waste into bacterial nanocellulose through enzymatic hydrolysis. They determined that the obtained nanocellulose was functionalised with black raspberry extract, which has a high antioxidant content. In addition, Sun et al. (2024) focused on increasing the nutritional value of agricultural industry by-products through bioprocessing. They stated that protein content and digestibility were increased by using fungi, yeast, bacteria, and enzymes, and toxins were eliminated. Thevarajah et al. (2024) noted that the use of food industry waste in *Spirulina* cultivation is a sustainable food source due to its high protein content. Wang et al. (2024) demonstrated that converting food waste into sustainable biomaterials using microalgae-based biorefinery methods is a practical approach. Kim and Doh (2024) analysed the structural properties of nanocellulose extracted from food by-products and demonstrated that this material can be utilised in the food, biomedical, and packaging industries. Within these determinations, Vilas-Franquesa et al. (2024) developed a guide called the 'Food By-Product Bioprocess Wheel' for industrial use, aiming to evaluate food waste using biotechnological methods.

Pereira et al. (2023) and Noor et al. (2024) reported in their studies that microwave and ultrasound-assisted extraction techniques are effective in obtaining antioxidant and antimicrobial components from small fruit and vegetable wastes, and Gong et al. (2024) reported that they increased the stability of polyphenols and increased their usability as food supplements by developing a pH-focused method. The recovery of bioactive components from seafood waste is considered an important issue, and Grasso et al. (2024) stated that antioxidant peptides were obtained from tuna waste by enzymatic hydrolysis. In addition, Vilas-Franquesa et al. (2024) reported that the fermentation process of mango peel increases the solubility of bioactive aglycones. Consumers' perceptions of food waste recycling are increasing daily, and this growing awareness has been found to have an impact on the acceptability of products in the market (Coderoni and Perito 2021). Nonetheless, evaluated from the consumer's perspective is stated that products obtained from simple or homogeneous wastes are more accepted, and the sustainable and health benefits of mixed wastes should be further clarified. However, Huang et al. (2024) reported that health-oriented values are more effective in promoting the adoption of these products.

Kim (2024) stated that South Korean food recycling regulations can be restrictive due to concerns about microbiological safety. Therefore, for food recovery to become more widespread worldwide, legislation and safety policies must play a transparent and supportive role. Newly developed technologies are crucial for maximising the benefits of food waste management. Yassin et al. (2021) determined the effectiveness of the high-pressure homogenisation method, which accelerates the release of bioactive components by breaking down the cell walls. Alternatively, Måge et al. (2023) found that spectroscopy and chemometric analysis methods increase sensitivity and efficiency in the industrial transformation of food waste. On the other hand, it is predicted that the integration of biotechnological approaches into the food cycle, specifically the fermentation of food waste into edible and nutritious products, will increase rapidly in the coming period (Rekdal et al. 2024).

DISCUSSION

The demonstrated efficiency and scalability potential of green extraction technologies such as ultrasound-assisted extraction, microwave-assisted extraction, and supercritical fluid extraction offer practical pathways for the food industry to adopt more sustainable and cost-effective methods for recovering bioactive compounds from diverse food waste streams, reducing reliance on hazardous solvents and energy-intensive processes (Dhenge et al. 2024; Herzyk et al. 2024; Roselli et al. 2024; Zheng et al. 2025). However it should be noted that the majority of these studies have been performed on relatively homogeneous food waste fractions, whereas the valorisation of heterogeneous and multi-component waste streams (closer to real-world industrial conditions) remains underexplored and requires further empirical validation (Zhang et al. 2024).

The development of tools like the food by-product bioprocess wheel facilitates the translation of enzymatic and fermentation-assisted extraction methods from

https://doi.org/10.17221/122/2025-CJFS

the laboratory to the industrial scale, providing industry innovators with actionable guidance to optimise valorisation strategies tailored to specific by-products (Vilas-Franquesa et al. 2024).

The valorisation of recovered bioactive compounds as natural antioxidants, antimicrobials, and functional food ingredients presents practical opportunities for replacing synthetic additives, thereby aligning with consumer demand for clean-label products and enhancing food safety and shelf life (Veneziani et al. 2017; Andrade et al. 2022; Enciso-Martínez et al. 2024).

The integration of probiotic fermentation with polyphenol extraction not only enhances the bioactivity and stability of the compounds but also supports the development of novel functional foods and nutraceuticals with combined health benefits, offering new product development avenues for the food sector (Moussaoui et al. 2021; Wang et al. 2024). Future research should further investigate how these synergistic processes perform under industrially relevant, heterogeneous waste conditions, where matrix complexity may influence both microbial activity and extraction yields.

Environmental impact assessments emphasise the importance of optimising extraction and encapsulation processes to minimise energy consumption and chemical use, thereby guiding policy and industrial practices toward more sustainable production models and supporting regulatory frameworks for green technologies (Pampuri et al. 2021; Nutrizio et al. 2024). In this regard, policy instruments and incentives may play a crucial role in facilitating the transition of green extraction technologies from controlled laboratory contexts to large-scale valorisation of mixed food waste streams.

The successful application of advanced extraction and bioprocessing techniques to a wide range of food industry by-products, including fruit peels, pomace, and cereal residues, highlights the broad applicability of these methods, encouraging cross-sector collaboration and innovation in waste management and resource recovery (Fărcaș et al. 2022; Nirmal et al. 2023; Sommer et al. 2023). Still, comprehensive evaluations that integrate process efficiency, scalability, consumer perception, and regulatory alignment are still limited, leaving an important knowledge gap that future studies must address in order to ensure practical and sustainable adoption at an industrial level.

CONCLUSION

It has been established that the reuse of food waste and by-products offers substantial advantages for sustainable development within the food, pharmaceutical, and nutraceutical sectors. Various extraction and transformation techniques, particularly non-thermal methods, have proven effective in recovering biologically active components, thereby providing nutritional value along with environmental and economic benefits. The integration of biotechnological applications, microbial fermentation, and innovative processing methods holds promise for utilising food waste in the production of functional foods, biomaterials, biofuels, and other value-added products. This potential is further enhanced by the ongoing advancement of renewable technologies. However, to obtain the maximum benefit from evaluating food waste, regulatory frameworks need to be developed, technological innovations should be encouraged, and consumer awareness should be increased. Eliminating safety concerns, optimising extraction processes, and establishing global policies that support the recovery of food waste are seen as the most fundamental ways to make these sustainable solutions more effective and widespread. As new approaches emerge in research, it is believed that the reuse of food waste, and thus the pursuit of a zero-waste target, will reduce raw material needs and increase added value in the food industry. Thus, the use of natural resources will decrease, and the concepts of environmental protection and sustainability will gain more prominence.

Environmental sustainability is a recurring emphasis, with life cycle assessments underscoring the importance of optimising process parameters and scaling up to realise meaningful reductions in carbon footprint and resource use. While some green technologies require high initial capital investment, their scalability and operational efficiencies offer promising economic feasibility, especially when balanced against the value of recovered bioactives and cost savings from waste disposal. Nonetheless, comprehensive and standardised environmental and economic evaluations remain limited across studies, highlighting a gap for future research.

Applications of recovered bioactive compounds are diverse and growing, encompassing functional foods, natural preservatives, active packaging, nutraceuticals, and even livestock feed enrichment. These applications align with consumer demand for natural, health-promoting ingredients and support circular economy models by valorising agro-industrial by-products. Challenges persist in ensuring product stability, regulatory approval, sensory acceptance, and consistent bioactive content, which must be addressed to facilitate industrial adoption.

https://doi.org/10.17221/122/2025-CJFS

The specific challenge at hand involves the complexities of actual multi-component food waste, which is made up of a combination of organic and inorganic substances that complicate conventional treatment methods (El-Mashad and Zhang 2007; Moreno-González and Ottens 2021). Although there have been advancements in techniques such as anaerobic digestion, pyrolysis, and hydrothermal treatments, significant gaps in knowledge persist regarding the effective integration of mechanical, chemical, and biological separation processes specifically designed for diverse food waste streams (Okopi et al. 2024; Al-Daas et al. 2024; Askarniya et al. 2024). There is ongoing debate about the most effective pretreatment combinations and their environmental impacts, with some studies supporting thermal-chemical methods while others focus on enzymatic or microbial strategies (Liyanage and Babel 2020; Ran et al. 2023; Eniyan et al. 2024). The absence of a unified agreement and the scarcity of techno-economic evaluations are barriers to the broader implementation of these integrated techniques (Giwa et al. 2022; García-Morales and Fernandez-Morales 2024).

Several studies demonstrate the effectiveness of combining mechanical comminution with enzymatic or microbial treatments to enhance solubilisation and recovery of valuable compounds, leading to improved biogas yields and material recovery (Al-Daas et al. 2024; Eniyan et al. 2024). Despite promising results, many integrated approaches face challenges in process optimisation and control due to the complexity of food waste composition. The heterogeneity of real food waste complicates the reproducibility and scalability of combined treatments, and inhibitory effects from accumulated salts or impurities are reported, limiting biological process efficiency (Al-Daas et al. 2024; Gallipoli et al. 2024).

Advanced pretreatment methods, including surfactant-assisted mechanical homogenisation, acoustic cavitation with oxidants, and enzymatic co-treatments, have shown significant improvements in solubilisation and biomethane production, indicating strong potential for enhancing downstream biological processes (Askarniya et al. 2024; Al-Daas et al. 2024; Eniyan et al. 2024). The use of thermal pretreatments combined with solid-liquid separation optimises substrate availability for anaerobic digestion (Gallipoli et al. 2024).

Emerging green extraction methods, including natural deep eutectic solvents (NADES), pulsed electric fields (PEF), and subcritical water extraction (SWE), offer environmentally friendly alternatives for recovering high-value bioactive compounds from food waste, aligning with circular economy principles (Majeed et al. 2024; Ristivojević et al. 2024; Roselli et al. 2024). These methods improve extraction yields while reducing toxic solvent use and energy consumption (Chatzimitakos et al. 2023; Mavai et al. 2025).

In summary, the literature strongly supports the potential of green extraction technologies combined with biotechnological processes to upcycle bioactive compounds from food industry waste in a sustainable manner. However, to fully realise industrial-scale implementation, there is a critical need for standardised protocols, robust scale-up studies, integrated environmental and economic assessments, and a deeper understanding of probiotic bioactivity mechanisms. Addressing these gaps will enable the food industry to effectively harness these innovations, contributing to sustainable food systems and circular economy objectives. The future direction involves enhancing process intensification, using AI-driven optimisation, and creating strong, scalable biorefineries that can effectively manage real multi-component food waste. These multidisciplinary strategies are crucial for improving valorisation results, meeting sustainability objectives, and facilitating circular bioeconomy models. Ongoing research should prioritise addressing scalability issues, improving environmental and economic evaluations, and developing pretreatment and separation technologies that can withstand variations in feedstock and contaminants.

REFERENCES

Adefegha S.A. (2018): Functional foods and nutraceuticals as dietary interventions in chronic diseases: Novel perspectives for health promotion and disease prevention. Journal of Dietary Supplements, 15: 977–1009.

Ahmad A., Imran A., Nadeem R., Islam F., Naz S., Suleria H. (2024): Extraction of protein and polyphenols from agro-industrial waste through eco-innovative technologies. In: Mehta S., Islam F., Imran A.: Innovations in Engineering and Food Science. Hershey, IGI Global Scientific Publishing: 263–277.

Al-Daas A., Alam M.Z., Azmi A.S. (2024): Acidic-enzymatic co-treatment of food waste for high sugar recovery and biogas production. Jurnal Teknologi (Sciences & Engineering), 86: 1–7.

Andrade M.A., Barbosa C.H., Shah M.A., Ahmad N., Vilarinho F., Khwaldia K., Silva A.S., Ramos F. (2022): Citrus by-products: Valuable source of bioactive compounds for food applications. Antioxidants, 12: 38.

Aqilah N.M.N., Rovina K., Felicia W.X.L., Vonnie J.M. (2023): A review on the potential bioactive components in fruits and vegetable wastes as value-added products in the food industry. Molecules, 28(6): 2631.

https://doi.org/10.17221/122/2025-CJFS

Ardra S., Barua M.K. (2022): Halving food waste generation by 2030: The challenges and strategies of monitoring the UN sustainable development goal target 12.3. Journal of Cleaner Production, 380: 135042.

Arcia P., Curutchet A., Pérez-Pirotto C., Hernando I. (2024): Upcycling fruit pomaces (orange, apple, and grape-wine): The impact of particle size on phenolic compounds' bioaccessibility. Heliyon, 10: e38737.

Askarniya Z., Kong L., Wang C., Sonawane S.H., Mąkinia J., Boczkaj G. (2024): Tuning of food wastes bioavailability as feedstock for bio-conversion processes by acoustic cavitation and SPC, SPS, or H_2O_2 as external oxidants. Chemical Engineering and Processing – Process Intensification, 195: 109626.

Azevedo E.S., Zapata Noreña C.P. (2024): Upcycling of the non-pomace residue of grape juice in the functionalization of polyelectrolyte complexes for the development of biodegradable freshness indicators. Food Hydrocolloids, 143: 108869.

Bangar S.P., Chaudhary V., Kajla P., Balakrishnan G., Phimolsiripol Y. (2024): Strategies for upcycling food waste in the food production and supply chain. Trends in Food Science & Technology, 143: 104314.

Bas-Bellver C., Barrera C., Betoret N., Seguí L. (2023): Physicochemical, technological and functional properties of upcycled vegetable waste ingredients as affected by processing and storage. Plant Foods for Human Nutrition, 78(4): 710–719.

Bejenaru L.E., Radu A., Segneanu A.-E., Biţă A., Manda C.-V., Mogoşanu G.D., Bejenaru C. (2024): Innovative strategies for upcycling agricultural residues and their various pharmaceutical applications. Plants, 13: 2133.

Bekavac N., Krog K., Stanić A., Šamec D., Šalić A., Benković M., Jurina T., Gajdoš Kljusurić J., Valinger D., Jurinjak Tušek A. (2025): Valorization of food waste: Extracting bioactive compounds for sustainable health and environmental solutions. Antioxidants, 14: 714.

Benvenutti L., Moura F.M., Zanghelini G., Barrera C., Seguí L., Zielinski A.A.F. (2025): An upcycling approach from fruit processing by-products: Flour for use in food products. Foods, 14: 153.

Bhatia S.K., Patel A.K., Yang Y.H. (2024): The green revolution of food waste upcycling to produce polyhydroxyalkanoates. Trends in Biotechnology, 42: 1273–1287.

Bravi E., De Francesco G., Sileoni V., Perretti G., Galgano F., Marconi O. (2021): Brewing by-product upcycling potential: Nutritionally valuable compounds and antioxidant activity evaluation. Antioxidants, 10: 165.

Caicedo-Paz A.V., Hucke H.U., Tropea A., Mondello L., Mussagy C.U. (2024): Win-win upcycling strategy for red araçá fruit waste: Process intensification and application of food-grade cyanidin-rich antioxidants. Future Foods, 11: 100535.

Chang Y., Shi X., He F., Wu T., Jiang L., Normakhamatov N., Sharipov A., Wang T., Wen M., Aisa H.A. (2022): Valorization of food processing waste to produce valuable polyphenolics. Journal of Agricultural and Food Chemistry, 70: 8855–8870.

Chatzimitakos T., Athanasiadis V., Kalompatsios D., Mantiniotou M., Bozinou E., Lalas S.I. (2023): Pulsed electric field applications for the extraction of bioactive compounds from food waste and by-products: a critical review. Biomass, 3: 367–401.

Chhandama M.V.L., Chetia A.C., Satyan K.B., Ao S., Ruatpuia J.V.L., Rokhum S.L. (2022): Valorisation of food waste to sustainable energy and other value-added products: A review. Bioresource Technology Reports, 17: 100945.

Coderoni S., Perito M.A. (2021): Approaches for reducing waste in the agricultural sector: An analysis of millennials' willingness to buy food with upcycled ingredients. Waste Management, 126: 283–290.

Costa C., Marques M., Martins A.M., Gonçalves L., Pinto P., Ribeiro H.M., Marto J., Paiva A. (2025a): Upcycling spent coffee grounds into bioactive extracts using new natural deep eutectic systems for sustainable topical formulations. ACS Sustainable Chemistry & Engineering, 13: 1906–1915.

Costa N.A., Chiocchetti G.M., Lepaus B.M., Silva J.M.S., Montenegro F.M., Camargo G.A., Macedo G.A., Macedo J.A. (2025b): Investigating the hypoglycemic potential of phenolic-rich extracts for upcycling into sugary processed foods. ACS Food Science & Technology, 5: 327–335.

Das P., Ganguly S., Ahmed S.R., Sherazee M., Margel S., Gedanken A., Rajabzadeh A.R. (2022): Carbon-dot biopolymer-based flexible functional films for antioxidant and food monitoring applications. ACS Applied Polymer Materials, 4: 9323–9340.

De Clercq D., Wen Z., Gottfried O., Schmidt F., Fei F. (2017): A review of global strategies promoting the conversion of food waste to bioenergy via anaerobic digestion. Renewable and Sustainable Energy Reviews, 79: 204–221.

Despoudi S., Bucatariu C., Otles S., Kartal C. (2021): Food waste management, valorization, and sustainability in the food industry. In: Galanakis C.M. (ed): Food Waste Recovery. 2nd Ed. Cambridge, Academic Press: 3–19.

Dhenge R., Rinaldi M., Ganino T., Lacey K. (2024): Recent and novel technology used for the extraction and recovery of bioactive compounds from fruit and vegetable waste. In: Selvamuthukumaran M. (ed): Wealth out of Food Processing Waste. Boca Raton, CRC Press: 162–187.

Díaz-Montes E., Castro-Muñoz R. (2021): Trends in chitosan as a primary biopolymer for functional films and coatings manufacture for food and natural products. Polymers, 13: 767.

Difonzo G., Grassi S., Paciulli M. (2022): Upcycling of agro-food chain by-products to obtain high-value-added foods. Foods, 11: 2043.

https://doi.org/10.17221/122/2025-CJFS

Ebrahimi P., Lante A. (2022): Environmentally friendly techniques for the recovery of polyphenols from food by-products and their impact on polyphenol oxidase: A critical review. Applied Sciences, 12: 1923.

EEA (2023): Environmental Statement 2023. Copenhagen, EEA. Available at: https://www.eea.europa.eu/en/analysis/publications/environmental-statement-2023 (accessed Dec 23, 2024).

El-Mashad H.M., Zhang R. (2007): Separation technologies for food wastewater treatment and product recovery. In: Waldron K. (ed): Handbook of waste management and co-product recovery in food processing. Sawston, Woodhead Publishing: 282–302.

Enciso-Martínez Y., Zuñiga-Martínez B.S., Ayala-Zavala J.F., Domínguez-Avila J.A., González-Aguilar G.A., Viuda-Martos M. (2024): Agro-industrial by-products of plant origin: Therapeutic uses as well as antimicrobial and antioxidant activity. Biomolecules, 14: 762.

Eniyan M.C., Edwin M., Banu J.R. (2024): Enhancing biomethane yield from food waste through surfactant-assisted mechanical pretreatment: An optimization approach. Journal of Renewable and Sustainable Energy, 16: 043102.

Fărcaș A.C., Socaci S.A., Nemeș S.A., Salanță L.C., Chiș M.S., Pop C.R., Borșa A., Diaconeasa Z., Vodnar D.C. (2022): Cereal waste valorization through conventional and current extraction techniques – An up-to-date overview. Foods, 11: 2454.

Faustino M., Veiga M., Sousa P., Costa E.M., Silva S., Pintado M. (2019): Agro-food by-products as a new source of natural food additives. Molecules, 24: 1056.

Fernandes A., Simões S., Ferreira I.M., Alegria M.J., Mateus N., Raymundo A., de Freitas V. (2022): Upcycling Rocha do Oeste pear pomace as a sustainable food ingredient. Molecules, 28: 179.

Fierascu I., Fierascu R.C., Sieniawska E. (2021): Advanced techniques for recovery of active compounds from food by-products. In: Bhat R. (ed): Valorization of Agri-Food Wastes and By-Products. Cambridge, Academic Press: 693–710.

Galanakis C.M. (2013): Emerging technologies for the production of nutraceuticals from agricultural by-products: A viewpoint of opportunities and challenges. Food and Bioproducts Processing, 91: 575–579.

Gallipoli A., Angelini F., Angelini S., Braguglia C.M., Montecchio D., Tonanzi B., Gianico A. (2024): Thermally enhanced solid–liquid separation process in food waste biorefinery: Modelling the anaerobic digestion of solid residues. Frontiers in Bioengineering and Biotechnology, 12: 1343396.

García-Morales J.L., Fernández-Morales F.J. (2024): Sustainable development of food waste biorefineries. Fermentation, 10: 301.

Giwa A.S., Sheng M., Zhang X., Wu Y., Bo H., Memon A.G., Bai S., Ali N., Ndungutse J.M., Kaijun W. (2022): Approaches for treating domestic wastewater with food waste and recovery of potential resources. Environmental Pollutants and Bioavailability, 34: 501–517.

Grasso F., Martínez M.M.A., Turrini F., Méndez Paz D., Vázquez Sobrado R., Orlandi V., Jenssen M., Lian K., Rombi J., Tiso M., Razzuoli E., Costas C., Boggia R. (2024): Antioxidant marine hydrolysates isolated from tuna mixed by-products: An example of fishery side streams upcycling. Antioxidants, 13: 1011.

Grimaldi M., Pitirollo O., Ornaghi P., Corradini C., Cavazza A. (2022): Valorization of agro-industrial by-products: Extraction and analytical characterization of valuable compounds for potential edible active packaging formulation. Food Packaging and Shelf Life, 33: 100900.

Gómez-García R., Campos D.A., Aguilar C.N., Madureira A.R., Pintado M. (2021): Valorization of food agro-industrial by-products: From the past to the present and perspectives. Journal of Environmental Management, 299: 113571.

Gong X., Wang M., Lu P., Zhou H. (2024): An improved pH-driven method for upcycling polyphenols from plants or by-products into foods. Foods, 13: 3945.

Liyanage T.U.H., Babel S. (2020): Thermal, ultrasonic and electrochemical pretreatment methods to enhance the solubilization of organic substance and methane generation in food waste. Journal of Material Cycles and Waste Management, 22: 1418–1426.

Herzyk F., Piłakowska-Pietras D., Korzeniowska M. (2024): Supercritical extraction techniques for obtaining biologically active substances from a variety of plant by-products. Foods, 13: 1713.

Huang W.S., Tsai T.Y., Lai K.L., Chen H.S. (2024): Analyzing consumer motivations and behaviors toward upcycled food from an environmental sustainability perspective. Agriculture, 14: 1967.

Idrishi R., Aggarwal D., Sharma V. (2022): Upcycling technologies in the food industry. In: Sehgal S., Singh B., Sharma V. (eds): Smart and Sustainable Food Technologies. Cham, Springer: 367–392.

Imeneo V., Piscopo A., Santacaterina S., De Bruno A., Poiana M. (2023): Sustainable recovery of antioxidant compounds from Rossa di Tropea onion waste and application as ingredient for white bread production. Sustainability, 16: 149.

Jaouhari Y., Travaglia F., Giovannelli L., Picco A., Oz E., Oz F., Bordiga M. (2023): From industrial food waste to bioactive ingredients: A review of the sustainable management and transformation of plant-derived food waste. Foods, 12: 2183.

Jiang Y., Xie Y., Xu X., Li Z., Henry C.J., Zhou W. (2024): Toward sustainable upcycling of side streams of purple bread wheat using dry fractionation. Food Chemistry, 458: 139838.

https://doi.org/10.17221/122/2025-CJFS

Kanwal N., Zhang M., Zeb M., Batool U., Khan I., Rui L. (2024): From plate to palate: Sustainable solutions for upcycling food waste in restaurants and catering. Sustainable Food Systems, 152: 104687.

Kim S.O. (2024): Review of food upcycling in South Korea: Regulation, limitations, and prospects. Food Science and Biotechnology, 32: 1–10.

Kim M., Doh H. (2024): Upcycling food by-products: Characteristics and applications of nanocellulose. Chemistry: An Asian Journal, 19: e202301068.

Kussmann M., Cunha D.H.A., Berciano S. (2024): Bioactive compounds for human and planetary health. Frontiers in Nutrition, 10: 1193848.

Leichtweis M.G., Oliveira M.B.P., Ferreira I.C.F.R., Pereira C., Barros L. (2021): Sustainable recovery of preservative and bioactive compounds from food industry bioresidues. Antioxidants, 10: 1827.

Low X.Y., Chong C.Y. (2024): Extraction of bioactive compounds from passion fruit waste and their potential applications in the food industry: A scoping review. Food Research, 8: 142–156.

Måge I., Wubshet S.G., Wold J.P., Solberg L.E., Böcker U., Dankel K., ... & Afseth N.K. (2023): The role of biospectroscopy and chemometrics as enabling technologies for upcycling of raw materials from the food industry. Analytica Chimica Acta, 1284: 342005.

Mahabeer G., Jin S. (2024): Upcycling food waste into biomaterials applicable to medical products. Sustainability, 16: 4473.

Majeed T., Shabir I., Srivastava S., Maqbool N., Dar A.H., Jan K., Pandey V.K., Shams R., Bashir I., Dash K.K., Hanan E., Wani N.R. (2024): Valorization of food wastes by implementation of subcritical water extraction: A comprehensive review. Trends in Food Science & Technology, 143: 104316.

Martí-Quijal F.J., Khubber S., Remize F., Tomasevic I., Roselló-Soto E., Barba F.J. (2021): Obtaining antioxidants and natural preservatives from food by-products through fermentation: A review. Fermentation, 7: 106.

Martillanes S., Rocha-Pimienta J., Gil M.V., Ayuso-Yuste M.C., Delgado-Adámez J. (2020): Antioxidant and antimicrobial evaluation of rice bran (*Oryza sativa* L.) extracts in a mayonnaise-type emulsion. Food Chemistry, 308: 125633.

Mavai S., Bains A., Sridhar K., Chawla P., Sharma M. (2025): Emerging deep eutectic solvents for food waste valorization to achieve sustainable development goals: Bioactive extractions and food applications. Food Chemistry, 462: 141000.

Moreno-González M., Ottens M. (2021): A structured approach to recover valuable compounds from agri-food side streams. Food and Bioprocess Technology, 14: 1387–1406.

Moussaoui T., Khali M., Madi N. (2021): Application of response surface methodology for the co-optimization of extraction and probiotication of phenolic compounds from pomegranate fruit peels (*Punica granatum* L.). Journal of Food Measurement and Characterization, 15: 3618–3633.

Nahi O., Siankevich S. (2023): Upcycling of cereal by-products: A sustainable opportunity to valorize wasted nutrients and derive bioactive compounds for human and animal nutrition and health. Chimia, 77: 858.

Negi T., Anand A., Samkaria S., Kaushik R. (2025): Bioactive compounds from food waste. In: Sirohi R., Tarafdar A., de Souza Vandenberghe L.P., Taherzadeh M.J., Pandey A. (eds): Sustainable Technologies for Food Waste Management. 1st Ed. Boca Raton, CRC Press: 31.

Nirmal N.P., Khanashyam A.C., Mundanat A.S., Shah K., Babu K.S., Thorakkattu P., Al-Asmari F., Pandiselvam R. (2023): Valorization of fruit waste for bioactive compounds and their applications in the food industry. Foods, 12: 556.

Noor A., Moyle P.M., Malik A., Ziora Z.M., Pant K.K. (2024): Transformative upcycling of fruit-vegetable waste for nutraceutical and pharmaceutical breakthroughs and circular economy evolution. Process Safety and Environmental Protection, 187: 1022–1036.

Nutrizio M., Dukić J., Sabljak I., Samardžija A., Biondić Fučkar V., Djekić I., Režek Jambrak A. (2024): Upcycling of food by-products and waste: Non-thermal green extractions and life cycle assessment approach. Sustainability, 16: 9143.

Okopi S.I., Wang J., Liang W., Kong W., Hu Y., Cui J., Guo X., Zhao W., Che L., Gu Z., Xu F. (2024): Experimental study and techno-economic analysis of co-processing system for treatment of food waste with various impurities. Bioresource Technology, 394: 130020.

Pampuri A., Casson A., Alamprese C., Di Mattia C.D., Piscopo A., Difonzo G., Conte P., Paciulli M., Tugnolo A., Beghi R., Casiraghi E., Guidetti R., Giovenzana V. (2021): Environmental impact of food preparations enriched with phenolic extracts from olive oil mill waste. Foods, 10: 980.

Pantelic L., Skaro Bogojevic S., Vojnovic S., Oliveira R., Lazic J., Ilic-Tomic T., Milivojevic D., Nikodinovic-Runic J. (2024): Upcycling of food waste streams to valuable biopigments pyocyanin and 1-hydroxyphenazine. Enzyme and Microbial Technology, 171: 110322.

Panzella L., Moccia F., Nasti R., Marzorati S., Verotta L., Napolitano A. (2020): Bioactive phenolic compounds from agri-food wastes: An update on green and sustainable extraction methodologies. Frontiers in Nutrition, 7: 60.

Park J.H., Kang D.Y., Park J.W., Jung H.Y., Lee Y.H., Kim D.H., Kwak J.K., Lee G.H., Choi Y.E. (2024): Novel approach to upcycling food processing biomass: Development of rice snacks using rice bran emulsifier. Food Science and Biotechnology, 34: 471–478.

Parra-Pacheco B., Cruz-Moreno B.A., Aguirre-Becerra H., García-Trejo J.F., Feregrino-Pérez A.A. (2024): Bioactive compounds from organic waste. Molecules, 29: 2243.

https://doi.org/10.17221/122/2025-CJFS

Patel A., Desai S.S., Mariam I., Enman J., Rova U., Christakopoulos P., Matsakas L. (2024): Innovative biorefinery approaches for the upcycling of post-consumer food waste in a circular bioeconomy context. Chemical Engineering Journal, 494: 152990.

Pereira A., Añibarro-Ortega M., Kostić M., Nogueira A., Soković M., Pinela J., Barros L. (2023): Upcycling quince peel into bioactive ingredients and fiber concentrates through multicomponent extraction processes. Antioxidants, 12: 260.

Pinela J., Añibarro-Ortega M., Barros L. (2024): Food waste biotransformation into food ingredients: A brief overview of challenges and opportunities. Foods, 13: 3389.

Ponjavic M., Filipovic V., Topakas E., Karnaouri A., Zivkovic J., Krgovic N., Mudric J., Savikin K., Nikodinovic-Runic J. (2023): Two-step upcycling process of lignocellulose into edible bacterial nanocellulose with black raspberry extract. Foods, 12: 2995.

Ran X.L., Zhang M., Wang Y., Adhikari B. (2019): Novel technologies applied for recovery and value addition of high value compounds from plant by-products: A review. Critical Reviews in Food Science and Nutrition, 59: 450–461.

Ran S., Zhang X., Jiang Y., Gao Y., Xu H., Yang H.Y., Xu J., Wang Y., Guo Y., Zhang H., Lyu Y. (2023): Methods for enhancing the properties of products from food waste via hydrothermal carbonation (HTC): Gradient-enzymatic-pretreatment-nitrogen-migration-strategy. Energy, 282: 128879.

Ramandani A.A., Sun Y.M., Lan J.C.W., Chen W.H., Chang J.S., Rachmadona N., Lim J.W., Khoo K.S. (2024): Upcycling nutrients derived from food waste via microalgae cultivation: A review on impacts on cellular compounds, economy and environment analyses for achieving circular bioeconomy. Biochemical Engineering Journal, 211: 109454.

Rathee S., Singh K.R.B., Mallick S., Singh J., Pandey S.S., Ojha A., Singh R.P. (2024): Smart alginate nanomaterials: Revolutionizing food across delivery, preservation, packaging, safety, and waste upcycling. Carbohydrate Polymer Technologies and Applications, 8: 100568.

Rekdal V.M., Villalobos-Escobedo J.M., Rodriguez-Valeron N., Olaizola Garcia M., Prado Vásquez D., Rosales A., Sörensen P.M., Baidoo E.E.K., de Carvalho A.C., Riley R., Lipzen A., He G., Yan M., Haridas S., Daum C., Yoshinaga Y., Ng V., Grigoriev I.V., Munk R., Wijaya C.H., Nuraida L., Damayanti I., Cruz-Morales P., Keasling J.D. (2024): Multi-omics analysis of a traditional fermented food reveals a byproduct-associated subpopulation of *Neurospora intermedia* for waste-to-food upcycling. bioRxiv.

Ristivojević P., Krstić Ristivojević M., Stanković D., Cvijetić I. (2024): Advances in extracting bioactive compounds from food and agricultural waste and by-products using natural deep eutectic solvents: A circular economy perspective. Molecules, 29: 4717.

Roth M., Jekle M., Becker T. (2024): Opportunities for upcycling cereal by-products with a special focus on distiller's grains. Trends in Food & Technology, 91: 282–293.

Roselli V., Pugliese G., Leuci R., Brunetti L., Gambacorta L., Tufarelli V., Piemontese L. (2024): Green methods to recover bioactive compounds from food industry waste: A sustainable practice from the perspective of the circular economy. Molecules, 29: 2682.

Rossi N., Grosso C., Delerue-Matos C. (2024): Shrimp waste upcycling: Unveiling the potential of polysaccharides, proteins, carotenoids, and fatty acids with emphasis on extraction techniques. Marine Drugs, 22: 153.

Sagar N.A., Pareek S., Sharma S., Yahia E.M., Lobo M.G. (2018): Fruit and vegetable waste: Bioactive compounds, their extraction, and possible use. Comprehensive Reviews in Food Science and Food Safety, 17: 512–531.

Sagar N.A., Pathak M., Sati H., Agarwal S., Pareek S. (2024): Advances in pretreatment methods for the upcycling of food waste: A sustainable approach. Journal of Cleaner Production, 147: 104413.

Sani I.K., Masoudpour-Behabadi M., Sani M.A., Motalebinejad H., Juma A.S.M., Asdagh A., Eghbaljoo H., Khodaei S.M., Rhim J.W., Mohammadi F. (2023): Value-added use of fruit and vegetable processing by-products for the manufacture of biodegradable food packaging films. Food Chemistry, 405: 134964.

Sharma V., Tsai M.L., Nargotra P., Chen C.W., Kuo C.H., Sun P.P., Dong C.D. (2022): Agro-industrial food waste as a low-cost substrate for sustainable production of industrial enzymes: a critical review. Catalysts, 12: 1373.

Sileoni V., Alfeo V., Bravi E., Belardi I., Marconi O. (2022): Upcycling of a by-product of the brewing production chain as an ingredient in the formulation of functional shortbreads. Journal of Functional Foods, 98: 105292.

Simitzis P.E. (2018): Agro-industrial by-products and their bioactive compounds – An ally against oxidative stress and skin aging. Cosmetics, 5(4): 58.

Singh G., Wu Y.F., Ahn S. (2022): Simple unsupervised object-centric learning for complex and naturalistic videos. Advances in Neural Information Processing Systems, 35: 18181–18196.

Socas-Rodríguez B., Álvarez-Rivera G., Valdés A., Ibáñez E., Cifuentes A. (2021): Food by-products and food wastes: Are they safe enough for their valorization? Trends in Food Science & Technology, 114: 133–147.

Sommer S., Hoffmann J.L., Fraatz M.A., Zorn H. (2023): Upcycling of black currant pomace for the production of a fermented beverage with *Wolfiporia cocos*. Journal of Food Science and Technology, 60: 1313–1322.

Sun X., Dou Z., Shurson G.C., Hu B. (2024): Bioprocessing to upcycle agro-industrial and food wastes into

https://doi.org/10.17221/122/2025-CJFS

high-nutritional value animal feed for sustainable food and agriculture systems. Resources, Conservation and Recycling, 201: 107325.

Tan Y.N. (2021): Upcycling of biomaterials from seafood waste and their applications. [PhD Thesis.] Singapore, Nanyang Technological University.

Thai S., Avena-Bustillos R.J., Alves P., Pan J., Osorio-Ruiz A., Miller J., Tam C., Rolston M.R., Teran-Cabanillas E., Yokoyama W.H., McHugh T.H. (2024): Influence of drying methods on health indicators of brewer's spent grain for potential upcycling into food products. Applied Food Research, 2: 100052.

Thevarajah B., Nimarshana P.H.V., Sandeepa G.D.S., Boopathy R., Ariyadasa T.U. (2024): Upcycling food processing industrial wastes in *Spirulina* cultivation: A perspective on the advancement of Sustainable Development Goal 12. Trends in Food Science & Technology, 149: 104537.

Thorsen M., Skeaff S., Goodman-Smith F., Thong B., Bremer P., Mirosa M. (2022): Upcycled foods: A nudge toward nutrition. Frontiers in Nutrition, 9: 1071829.

Thorsen M., Mirosa M., Skeaff S., Goodman-Smith F., Bremer P. (2024): Upcycled food: How does it support the three pillars of sustainability? Trends in Food Science & Technology, 143: 104269.

UNEP (2019): UN Calls for Urgent Rethink as Resource Use Skyrockets. Available at: https://www.unep.org/news-and-stories/press-release/un-calls-urgent-rethink-resource-use-skyrockets (accessed Dec 23, 2024).

UNEP (2022): Annual Report 2021. Available at: https://www.unep.org/resources/annual-report-2021 (accessed Dec 23, 2024).

Veneziani G., Novelli E., Esposto S., Taticchi A., Servili M. (2017): Applications of recovered bioactive compounds in food products. In: Galanakis C.M. (ed): Olive Mill Waste. Cambridge, Academic Press: 231–253.

Vilas-Boas A.A., Pintado M., Oliveira A.L.S. (2021): Natural bioactive compounds from food waste: Toxicity and safety concerns. Foods, 10: 1564.

Vilas-Franquesa A., Fryganas C., Casertano M., Montemurro M., Fogliano V. (2024a): Upcycling mango peels into a functional ingredient by combining fermentation and enzymatic-assisted extraction. Food Chemistry, 434: 137515.

Vilas-Franquesa A., Montemurro M., Casertano M., Fogliano V. (2024b): The food by-products bioprocess wheel: A guidance tool for the food industry. Trends in Food Science & Technology, 152: 104652.

Wang J., Wang Y., Xiao M., Liang Q., Yang S., Liu J., Zhang Y., Mou H., Sun H. (2024a): Upcycling food waste into biorefinery production by microalgae. Chemical Engineering Journal, 484: 149532.

Wang Y., Wang C., Shi J., Zhang Y. (2024b): Effects of derivatization and probiotic transformation on the antioxidative activity of fruit polyphenols. Food Chemistry: X, 23: 101776.

Wunderlich S.M., Martinez N.M. (2018): Conserving natural resources through food loss reduction: Production and consumption stages of the food supply chain. International Soil and Water Conservation Research, 6: 331–339.

Xiao N., Kong L., Wei M., Hu X., Li O. (2024): Innovations in food waste management: From resource recovery to sustainable solutions. Waste Disposal & Sustainable Energy, 6: 401–417.

Yassin D.A., Nasim M.J., Abraham A.M., Keck C.M., Jacob C. (2021): Upcycling culinary organic waste: Production of plant particles from potato and carrot peels to improve the antioxidative capacity. Current Nutraceuticals, 2: 62–70.

Zhang M., Zeiss M.R., Geng S. (2015): Agricultural pesticide use and food safety: California's model. Journal of Integrative Agriculture, 14: 2340–2357.

Zhang G., Li Z., Charalampopoulos D. (2024): Upcycling of melon seed (*Cucumis melo* L.) oil processing by-product: Evaluation of the functional properties and nutritional components as novel ingredient. Chemical and Biological Technologies in Agriculture, 11: 101.

Zheng S., Huang Z., Dong L., Li D., Hu X., Chen F., Ma C. (2025): Sustainable extraction technology of fruit and vegetable residues as novel food ingredients. Foods, 14: 331.

Received: July 29, 2025
Accepted: September 21, 2025
Published online: December 18, 2025