

Innovative valorization of vegetable oil industry by-products for bioactive resources in sustainable circular bioeconomy: A systematic review

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Abstract

This systematic review explores recent advancements in the valorization of vegetable oil industry by-products within the framework of a sustainable circular bioeconomy. Emphasizing green extraction technologies along with integrated biorefinery approaches, the study highlights the potential to recover a wide range of bioactive compounds, including polyphenols, carotenoids, phytosterols, and dietary fibres from residues like seed cakes, glycerol, soapstocks, and press residues. These bioactives exhibit significant health-promoting properties, such as anti-inflammatory, antioxidant, and antimicrobial activities, supporting applications across food, nutraceutical, pharmaceutical, and cosmetic sectors. Despite challenges in scalability, process optimization, and regulatory compliance, ongoing innovations and supportive policies are fostering industrial adoption. Moreover, this review underscores the critical role of environmentally friendly, resource-efficient strategies in reducing waste, lowering environmental impact, and creating economic value—thereby advancing sustainable development goals. Future perspectives focus on process integration, policy support, and interdisciplinary research to fully harness vegetable oil by-products, promoting a resilient, eco-friendly bioeconomy.

1 Introduction

1.1 Overview of the vegetable oil industry and its economic importance

Vegetable oils are derived from a diverse range of plant sources and play a vital role in global food systems, primarily used for cooking and food processing. Common sources include African oil palm, maize, olive, peanut, rapeseed, soybean, and sunflower. For instance, vegetable oil is a key ingredient in products like margarine, an artificial butter substitute. The primary reason for cultivating oilseed crops is their oil content, which varies widely among different crops—wheat, for example, has only 1–2% oil, whereas oilseeds like soybean contain about 20%, and sunflower and rapeseed over 40% (Murphy, 2024). Major edible oil sources such as soybeans, sunflowers, rapeseed, cottonseed, and peanuts are rich in bioactive compounds, including triglycerides, saturated and unsaturated fatty acids, polyphenolics, flavonoids, phytosterols, phospholipids, vitamins, and minerals. These bioactive constituents confer various health benefits, such as cardiovascular protection, anticancer effects, anti-inflammatory properties, and immune modulation (Nollet & Ahamad, 2024).

Globally, vegetable oils are essential for providing calories and essential nutrients to populations, with over 90% of production contributing significantly to food security. However, the rapid expansion of soybean and palm oil cultivation in tropical regions has raised environmental concerns, including loss of biodiversity and increased greenhouse gas emissions. To ensure the sustainability of these resources for future generations, it is crucial that the entire lifecycle—from cultivation and processing to consumption—is managed responsibly, prioritizing environmental preservation while meeting nutritional demands (Zio et al., 2025).

1.2 Bioactive compounds and their role in health

Vegetable oils have gained attention not only for their nutritional value but also for their ability to incorporate phenolics and other bioactive compounds through advanced stabilization techniques. These strategies not only preserve oil quality but also enhance its health-promoting properties. Innovative technologies aim to maximize extraction efficiency and actively fortify oils with bioactives such as phenolics, which offer antioxidant, anti-inflammatory, and antimicrobial benefits, thereby adding value beyond traditional preservation methods (Montoro-Alonso et al., 2025).

1.3 Environmental challenges and waste generation

The rapid growth of the global population, coupled with urbanization and industrialization, has led to an alarming increase in waste production. These wastes are often discarded into the environment without adequate treatment, posing serious ecological and health risks. Industrial and municipal wastes are of comparable danger levels; however, industrial waste management presents unique challenges. Industries often utilize raw resources extracted directly from the environment without sustainable practices, leading to resource depletion. Concurrently, waste products generated at the end of manufacturing processes—such as landfilling or incineration—further pollute ecosystems, exacerbate resource scarcity, and contribute to environmental degradation (Karuppiah et al., 2023).

In agricultural economies like India, effective management of residues from crop production is essential. Annually, approximately 500 million tons of agricultural waste are produced in India alone. This sector is responsible for over 13% of the country's greenhouse gas emissions, surpassing the global average. Valorization of agricultural residues presents opportunities for producing bioenergy and value-added products, supporting sustainable waste management and fostering a circular economy. Currently, residues are mainly used for biofuel production and solid bioenergy, with the added benefit of reducing environmental impacts and promoting resource recovery (Mahmudul et al., 2017; Reddy et al., 2025).

1.4 Oilseed by-products as sustainable resources

The cultivation and processing of oilseeds inherently generate large volumes of by-products, traditionally viewed as waste. However, these residues—such as seed cakes, press residues, glycerol, soapstocks, and distillates—are increasingly recognized as valuable lignocellulosic resources for biofuel production. Through various pretreatment methods—such as acid, alkali, hydrothermal, deep eutectic solvents, and steam explosion—these materials can be converted into biofuels like ethanol, methane (biogas), bio-oil, butanol, and hydrogen via thermochemical or biological processes. This approach not only creates a circular value chain within the oilseed system but also supports sustainable energy production and resource utilization (Yong & Wu, 2022).

1.5 Circular bioeconomy and sustainability

A circular bioeconomy emphasizes the reuse and recycling of waste streams from renewable biological resources, transforming them into energy or new materials through either open- or closed-loop

processes. The core principle is sustainability—using renewable inputs to maintain resource availability and minimize environmental impact. Although the concept of circularity is inherent in nature, its application in the modern economy requires innovation and systemic change. Implementing circular bioeconomy models encourages the replacement of environmentally harmful practices with sustainable alternatives, reshaping market structures and product development. For example, substituting fossil fuels with bio-based fuels like biodiesel and bioethanol, or developing new bio-derived products through genetic engineering and microbial biomass, exemplifies this shift. These innovations have the potential to revolutionize traditional sectors, fostering a more sustainable and resilient economy (Niewiadomski et al., 2025).

1.6 Aim and scope of this systematic Review

The aim of this systematic review was to comprehensively assess recent advancements in the valorization of by-products generated from the vegetable oil industry, focusing on sustainable extraction methods, biorefinery technologies, and applications of bioactive compounds. The scope includes examining studies published from 2007 to 2026 that explore the utilization of residues such as seed cakes, glycerol, soapstocks, and processing by-products across various sectors, including food, nutraceuticals, pharmaceuticals, and cosmetics. This review aims to identify innovative approaches that promote environmental sustainability, waste reduction, and added economic value, thereby supporting the development of a circular bioeconomy within the vegetable oil sector.

1.7 Question to be answered

What are the latest strategies and technologies for valorization of the vegetable oil industry by-products, and how can these approaches promote sustainability, reduce waste, and add value within a circular bioeconomy framework?

1.8 Novelty of this Review

This review is novel in its integration of cutting-edge green extraction techniques, biorefinery models, and interdisciplinary approaches to valorise diverse vegetable oil residues. It emphasizes the transition toward sustainable, eco-friendly processes that not only recover health-promoting bioactives but also support environmental conservation and economic development, offering new insights into the potential of underutilized by-products within a circular bioeconomy framework.

2 Methodology

This systematic review was conducted following established guidelines to ensure a comprehensive and unbiased synthesis of current research on the valorization of vegetable oil industry by-products within a circular bioeconomy framework. In accordance with PRISMA guidelines, the methodology involved the following steps:

2.1 Literature search strategy

An extensive literature search was performed across multiple electronic databases, including PubMed, Scopus, Web of Science, and Google Scholar, covering publications from 2007 until 2026. The search employed a combination of keywords and Boolean operators such as: "vegetable oil by-products," "bioactive compounds," "valorization," "green extraction," "biorefinery," "circular bioeconomy," and related synonyms. Additional sources included references from relevant review articles and grey literature to ensure comprehensiveness in English-language.

2.2 Inclusion and exclusion criteria

Studies were included if they focused on the extraction, recovery, or valorization of bioactive compounds from vegetable oil industry by-products, presented novel or emerging valorization strategies, technologies, or biorefinery models, and were published in peer-reviewed journals, conference proceedings, or credible reports in English. Conversely, studies were excluded if they were limited to theoretical discussions without experimental validation, focused solely on waste management without bioactive compound recovery, or were duplicates, reviews without new data, or lacked sufficient methodological detail.

2.3 Selection process

All retrieved records were thoroughly screened using a reference management system, complemented by manual screening to identify and exclude unreferenced or duplicate entries. Two independent reviewers carefully examined the titles and abstracts to assess their eligibility for inclusion in this systematic review.

2.4 Data extraction and synthesis

Two independent reviewers screened titles and abstracts for relevance, followed by full-text assessment. Discrepancies were resolved through discussion or consultation with a third reviewer. Extracted data included study objectives, types of by-products examined, extraction methodologies, target bioactive compounds, key findings, and limitations.

2.5 Quality Assessment

The methodological quality of the included studies was appraised with checklist for experimental design, extraction efficiency, environmental sustainability, and potential applications.

3 Results and Discussion

3.1 Study selection

As demonstrated in Fig. 1, the initial search resulted in 9,460 records. Following the removal of duplicates and ineligible entries, 924 unique records were available for further screening. From these, 133 reports were selected for retrieval, and ultimately, 83 reports were included in the review.

3.2 Vegetable oil industry by-products: Types, composition, and current management

The vegetable oil industry produces a substantial volume of by-products throughout the processes of oil extraction, refining, and processing. Traditionally regarded as low-value residues, these by-products are increasingly recognized as valuable resources due to their rich chemical and biological compositions. Gaining a comprehensive understanding of the different types of by-products, their compositional characteristics, and current management practices is crucial for developing sustainable valorization strategies within a circular bioeconomy framework. Moreover, we explore the health-promoting properties of these compounds and discuss advanced delivery systems—such as nanoemulsions and encapsulation—that are essential for stabilizing these bioactives for applications in nutraceuticals, functional foods, and pharmaceuticals (Costa et al., 2022).

3.2.1 Types of vegetable oil industry by-products

The processes involved in the extraction and refining of vegetable oils generate various secondary streams, each with distinct nutritional and functional properties.

3.2.1.1 Seed cakes and meals

Seed cakes and meals are the solid residues left after mechanical pressing or solvent extraction of oilseeds such as soybean, sunflower, rapeseed, palm kernel, cottonseed, and groundnut. Produced in large quantities, these by-products are characterized by high protein and fiber content. Besides their nutritional value, seed cakes and meals contain significant amounts of phenolic compounds, residual lipids, and bioactive peptides, making them promising raw materials for nutraceutical and functional food applications (Grahovac et al., 2025; Nemli et al., 2025).

3.2.1.2 Oil press residues

Oil press residues include partially defatted solids, filter cakes, and sludge generated during oil extraction and clarification processes. These materials are rich in residual oils, phospholipids, antioxidants, and other minor bioactive components. While their heterogeneous composition and high moisture content pose challenges for handling and disposal, they also present valuable opportunities as feedstocks for bioactive compound recovery and biorefinery-based valorization (Nemli et al., 2025).

3.2.1.3 Glycerol, soapstocks, and other secondary streams

Secondary by-products such as crude glycerol, soapstocks, fatty acid distillates, and deodorizer distillates are generated during oil refining and biodiesel production. Crude glycerol, in particular, is a significant by-product with applications in fermentation, chemical synthesis, and pharmaceuticals. Soapstocks and deodorizer distillates are rich in free fatty acids, tocopherols, sterols, and other minor

lipophilic bioactives, making them valuable sources for extracting functional ingredients (Chellamboli et al., 2025).

3.2.2 Chemical and biological composition of vegetable oil industry by-products

Vegetable oil industry by-products are a rich source of diverse chemically and biologically active compounds. These include phenolic compounds, natural antioxidants, dietary fibers, residual lipids, proteins, peptides, and essential micronutrients. Phenolic compounds and antioxidants play a crucial role in conferring anti-inflammatory, antimicrobial, and oxidative stress-reducing properties. Meanwhile, dietary fibers and bioactive lipids support gut health and help regulate metabolic processes. The specific composition of these by-products varies depending on factors such as the type of oilseed, extraction techniques, and processing conditions, which in turn influence their functional properties and potential applications (Chellamboli et al., 2025; Sahin, 2023).

3.2.3 Current utilization and limitations of vegetable oil industry by-products

3.2.3.1 Current uses

Currently, most by-products generated by the vegetable oil industry are employed in low-value applications. Seed cakes and meals are predominantly used as animal feed, owing to their high protein content. Other by-products are utilized in bioenergy production, composting, or serve as organic fertilizers. While these practices help in reducing waste, they do not fully harness the bioactive potential of these materials. This underutilization highlights the need for innovative approaches to valorize these by-products more effectively, unlocking their full range of bioactive compounds for sustainable and high-value applications (Nemli et al., 2025).

3.2.3.2 Limitations and environmental impacts

Despite ongoing utilization efforts, several significant limitations persist in current management practices. Inadequate processing techniques, inefficient recovery methods, and limited adoption of advanced technologies often result in the underexploitation of valuable bioactive compounds. Additionally, improper disposal of oil industry waste can pose serious environmental risks, including soil and water contamination, increased greenhouse gas emissions, and odor issues. These challenges underscore the urgent need for innovative, sustainable, and value-added valorization strategies that not only reduce environmental impact but also enhance economic and functional benefits. Developing such approaches is essential for advancing the environmentally responsible and economically viable management of vegetable oil industry by-products (Grenier et al., 2021; Sharma et al., 2022).

Figure 2 illustrates the experimental design of innovative valorization of vegetable oil industry by-products for bioactive resources in sustainable circular bioeconomy, with an overview of the integrated processes and strategies employed to extract and utilize bioactive resources, emphasizing the pathway

toward a sustainable circular bioeconomy. The figure serves as a visual guide to understand how various techniques and approaches are interconnected to enhance resource recovery, reduce waste, and promote environmental and economic sustainability within the vegetable oil sector.

3.3. Innovative valorization strategies

The food processing industry has experienced significant growth over the past decade, becoming one of the fastest-expanding sectors globally. However, this expansion is accompanied by substantial waste generation; approximately 20% to 30% of raw materials processed result in waste during production. Specifically, the fruit and vegetable industry contributes between 25% and 30% of the total waste stream, accounting for approximately 90% to 92% of the by-products generated during operations (Khan et al., 2024). These processing by-products are rich sources of bioactive compounds, including polyphenols, vitamins, minerals, bioactive peptides, dietary fibers, and essential oils, many of which possess potent antioxidant, nutraceutical, and antimicrobial properties. Fruit and vegetable peels, in particular, contain abundant bioactive compounds that may help reduce the risk of cardiovascular diseases and other physiological dysfunctions.

Strategic extraction and valorization of these phytochemicals through advanced technologies enable the transformation of low-value waste into high-value functional ingredients suitable for food fortification, nutraceutical formulations, and pharmaceutical applications. This review explores and compares both conventional and non-conventional extraction methodologies, such as microwave-assisted extraction (MWAE), ultrasound-assisted extraction (UAE), pulsed electric fields (PEF), pulsed electric heating (PEH), pressurized liquid extraction (PLE), supercritical fluid extraction (SFE), pressurized hot water (PHW), high hydrostatic pressure (HHP), and enzyme-assisted extraction (EAE). These innovative techniques have demonstrated higher extraction efficiencies, maximizing the value-added potential of fruit and vegetable wastes while promoting environmental sustainability and supporting a circular economy. The adoption of green solvents and non-conventional extraction methods is gaining popularity due to their environmental benefits and reduced dependence on harmful organic and inorganic solvents (Halahlah et al., 2025).

Traditional extraction techniques for isolating bioactive compounds—such as pectin, carotenoids, anthocyanins, antioxidants, phenolic acids, flavonoids, proteins, polysaccharides, dietary fibers, and essential oils—generally involve methods like Soxhlet extraction, maceration, percolation, and steam distillation. These processes often rely on hydroethanolic solvents and are typically time-consuming, highlighting the need for more efficient and sustainable extraction approaches.

3.3.1 Ultrasound-assisted extraction (UAE)

Ultrasound-assisted extraction (UAE) is an advanced, non-thermal extraction technique that utilizes acoustic waves generated in the solvent. These waves induce the formation of cavitation bubbles, which burst at the surface of the fruit and vegetable waste, disrupting cell walls and facilitating the release of

phenolic bioactive compounds into the solvent. The efficiency of UAE is optimized by carefully controlling parameters such as solvent concentration, solvent-to-sample ratio, extraction time, temperature, frequency, and power (Kaur et al., 2022). For instance, the extraction of phenolic compounds from mango peels using this technique involved a 50% aqueous ethanol solution, with a solid-to-liquid ratio of 1:30, at 45°C, and an ultrasound amplitude of 30%. After a treatment duration of 10 minutes, this method yielded the highest phenolic content of 35.5 mg GAE/g and achieved 92% antioxidant activity (Kaur et al., 2022).

3.3.2 Microwave-assisted extraction (MWAE)

Microwave-assisted extraction (MWAE) is a rapid and efficient technique that uses microwave energy to heat the solvent and plant or fruit matrices, thereby accelerating the release of bioactive compounds such as phenolics, flavonoids, and antioxidants. The method benefits from uniform heating and reduced extraction time compared to conventional techniques, making it environmentally friendly and cost-effective. MWAE operates by causing cell wall rupture and enhancing solvent penetration, which facilitates the release of target compounds into the solvent. Optimization of parameters such as microwave power, extraction time, solvent type, and solvent-to-sample ratio is crucial for maximizing yield and bioactivity. Recent studies have demonstrated the effectiveness of MWAE in extracting valuable bioactive compounds from various plant materials, including fruit peels and seeds, with improved efficiency and sustainability (Melikoglu, 2025). This technique holds significant promise for industrial applications in food, pharmaceuticals, and nutraceuticals, aligning with green chemistry principles and sustainable practices.

3.3.3 Supercritical Carbon Dioxide Extraction (SFE)

Supercritical fluid extraction (SFE) is primarily utilized for extracting volatile compounds from various matrices. This technique involves using supercritical fluids—such as carbon dioxide (CO₂) and water (H₂O)—at or near their critical temperature and pressure to efficiently recover bioactive compounds from solid plant materials. In the context of the tomato processing industry, tomato peel and seed waste are rich sources of high-value bioactive compounds, notably lycopene. Studies have shown that when lycopene is extracted from these by-products using supercritical CO₂ (SC-CO₂), the (Z)-lycopene content in the oleoresin reached 69%, which is higher than that obtained through conventional hexane extraction. Research comparing SC-CO₂ and hexane extraction methods revealed that SC-CO₂ not only offers a greener, more sustainable approach for extracting bioactive compounds but also enhances the health benefits of the extracted substances (da Silva & Jorge, 2017; Ubeyitogullari & Ciftci, 2022).

3.3.4 Pressurized liquid extraction (PLE)

Pressurized liquid extraction (PLE) is recognized as a high-throughput and environmentally friendly technique for the sustainable extraction of bioactive compounds from natural sources and plant matrices. Comparative studies between PLE, Soxhlet extraction, and traditional maceration methods have demonstrated that PLE is the most economical approach for isolating bioactive compounds from passionfruit rinds, particularly at a temperature of 60°C and using 70% ethanol as the solvent. However,

during the process, an issue of pipeline blockage was observed due to the gelatinization of pectin present in the passionfruit rinds. To address this, a pectin extraction step was proposed. It is important to note that higher temperatures are typically employed to accelerate extraction and disrupt interactions between analytes and the matrix. Nevertheless, key parameters such as solvent type, temperature, extraction time, repletion, and pressure significantly influence the efficiency and effectiveness of the process (Alvarez-Rivera et al., 2020).

3.3.5 Enzyme-assisted extraction (EAE)

Enzyme-assisted extraction (EAE) has emerged as an innovative and environmentally friendly technology for efficiently extracting phytochemicals from agri-food by-products. This targeted extraction leverages specific microorganisms such as bacteria, fungi, nematodes, or earthworms, which possess unique capabilities to decompose complex organic matter and release valuable bioactive compounds. Additionally, these biological agents play a crucial role in controlling postharvest fungal infections. A recent study evaluated the potential of EAE as a green technology for extracting bioactive compounds from olive leaves (*Olea europaea*) for possible industrial-scale applications (Vardakas et al., 2024). The process involved three enzymes—Celluclast, Pectinex XXL, and Viscozyme L—applied in various dose combinations under optimized conditions, including an incubation period of 120 minutes, temperature, and pressure. The resulting extracts were characterized based on total polyphenols (TP) and total antioxidant activity (AA). The findings clearly demonstrated that enzyme-assisted extraction significantly enhances polyphenol recovery from olive leaves, especially when employing multiple enzyme combinations. Notably, this enzymatic approach, combined with organic solvent-free methods, offers an environmentally sustainable alternative for phytochemical extraction (Łubek-Nguyen et al., 2022).

3.4. Chemical & biotechnological valorization approaches

Biotechnological valorization of agro-food waste (AFW)

The rise of industrialization and modernization has resulted in the generation of vast quantities of waste, leading to significant environmental challenges. Improper disposal and poor management of agro-food wastes can contaminate ecosystems, pose risks to human and animal health, and contribute to water pollution and aesthetic degradation. A substantial portion of agro-food waste remains untreated and underutilized, often being disposed of through burning, dumping, or unintentional landfilling. These practices increase greenhouse gas emissions and exacerbate climate change. Globally, approximately 15% of all waste originates from agricultural activities, making it a major contributor to pollution from the agriculture and agro-food processing sectors (Mishra et al., 2023).

In recent years, the valorization of agro-food waste—recovering valuable compounds and bioactives—has gained significant attention as an effective and environmentally sustainable strategy. Advances in recovery systems have made this approach increasingly feasible, offering benefits such as reduced environmental impact, decreased waste disposal burdens, and the creation of value-added bio-based products. Plant-derived agro-food wastes are rich sources of diverse bioactive compounds, including flavonoids, uronic acids, quercetin, polyphenols, carotenoids, anthocyanins, gallic acid, catechin, rutin,

ferulic acid, vanillin, sugars, and limonoids. These compounds have a wide range of applications, including nutraceuticals and functional foods, active pharmaceutical ingredients (APIs), cosmeceuticals, cosmetics, personal care products, and biodegradable materials (Varadavenkatesan et al., 2024).

To extract these bioactives efficiently, various techniques have been developed, such as solid-liquid extraction, ultrasonic-assisted extraction, subcritical water extraction, microwave-assisted extraction, supercritical fluid extraction, fermentation, and enzymatic processes. Each method offers distinct advantages and can be tailored according to the specific properties of the agro-food waste and the targeted compounds. Optimizing parameters like solvent type, extraction temperature, pressure, and duration is essential to maximize yield and purity while minimizing energy consumption and environmental impact.

Moreover, the pursuit of sustainable energy solutions has intensified, driven by the urgent need for decarbonization and climate change mitigation. Agricultural wastes often contain significant amounts of lignocellulose—including hemicellulose and cellulose—which, upon complete hydrolysis, produce simple sugars suitable for fermentation into bioenergy within zero-waste biorefinery systems. Agro-waste biorefineries are vital components of a circular bioeconomy, leveraging technological advancements to address biotechnological challenges and promote resource efficiency and sustainability (Capanoglu et al., 2022).

3.5 Valorization of fermented food wastes and by-products

Fermented food wastes are generated globally in large quantities, resulting in an excess of residual biomass that can serve as a valuable raw material for the extraction of important chemicals, fermentable sugars, polyphenols, and bioactive peptides. These compounds are essential for the synthesis of various bioproducts, contributing to waste reduction and adding economic value to industrial processes. The potential to synthesize bioproducts and extract bioactive compounds from fermentation-derived waste materials is significant, as many of these substances possess diverse biological properties that make them suitable for use as dietary supplements with potential health benefits. Different categories of fermented food waste and by-products—such as vegetable residues, bread waste, dairy processing leftovers, and brewing or winery by-products—can undergo various pre-treatment and extraction methodologies. These processes facilitate the recovery of bioactive compounds associated with documented health benefits and enable their application across multiple technological fields. Residual biomass from fermentation processes is rich in primary and secondary metabolites, allowing the production of valuable compounds such as amino acids, bioplastics derived from biopolymers, oleochemicals from natural lipids and fats, biofuels, and other bioactive-rich wastes containing terpenoids and flavonoids. For instance, molecules like acetone and ethanol can now be synthesized through metabolic engineering approaches, offering sustainable strategies for environmentally friendly compound production (Faria et al., 2023).

Furthermore, residues from fermented beverage production, including winery and brewery by-products, represent abundant sources of bioactive compounds, such as flavonoids, phenolic compounds, proteins,

and both soluble and insoluble dietary fibers. These phytochemicals exhibit notable biological activities, including antioxidant, anti-hyperglycemic, anti-hyperlipidemic, and cardioprotective effects (Faria et al., 2023). The valorization of these fermented residues not only facilitates the synthesis of high-value products but also generates residues rich in metabolites, extracellular enzymes, and other microbial metabolites, which have diverse applications. Additionally, the development of cleaner fuels—such as bioethanol—can be advanced by optimizing environmentally friendly refining technologies. For example, sugarcane juice is already used to produce bioethanol, although this substrate competes with food industries (Munasinghe & Khanal, 2011). Overall, the valorization of fermented food wastes and by-products holds great promise for sustainable development, environmental preservation, and the creation of valuable bio-based products.

3.6 Enzymatic hydrolysis and microbial fermentation

Bioactive peptides are biomolecules derived from proteins, typically comprising 2 to 20 amino acids, and are known for their diverse biological activities, including antihypertensive, antioxidant, and antimicrobial effects. These peptides are naturally embedded within their parent proteins in an inactive, encrypted form and must be liberated to manifest their bioactivity. Several methods exist for releasing these peptides, with biotechnological approaches being particularly advantageous. Among these, enzymatic hydrolysis and microbial fermentation are the most prominent techniques employed for this purpose (Cruz-Casas et al., 2021).

Food processing techniques such as maturation and heating can also facilitate the production of bioactive peptides. For instance, cooking foods at high temperatures (60–80°C) can increase protein accessibility, allowing endogenous enzymes to hydrolyze proteins more rapidly and efficiently. However, when temperatures exceed 100°C, peptides can be obtained from plasma proteins, where they are present in micromolar or nanomolar concentrations. These peptides are then isolated, purified, and assessed for their bioactivity. Microbial fermentation and enzymatic hydrolysis remain the most widely used biotechnological methods for the targeted release of bioactive peptides, offering controlled and efficient means of peptide generation (Peres Fabbri et al., 2024).

Enzymatic hydrolysis involves the use of commercial enzymes to liberate bioactive peptides from protein sources. These enzymes cleave specific peptide bonds within the protein structure, thereby releasing encrypted peptides and activating their biological properties. Enzymatic activity begins when the enzyme first binds to its substrate, forming an enzyme-substrate complex, before catalysis proceeds. Enzymes possess highly specific active sites containing two types of functional residues: those that form temporary bonds with the substrate (binding sites) and those that facilitate the catalytic reaction (catalytic sites). The stability of the enzyme-substrate complex is maintained through hydrogen bonds, hydrophobic interactions, and Van der Waals forces. Once the complex attains the correct conformation, it effectively catalyses the hydrolysis of proteins, releasing bioactive peptides (Cruz-Casas et al., 2021). Proteolytic enzymes can be derived from animal, plant, or microbial sources. However, enzymes from animal and plant origins present certain limitations. Microbial sources, on the other hand, offer advantages such as enhanced stability, faster production processes, and simpler nutritional

requirements. Additionally, microorganisms can be genetically and environmentally manipulated to produce enzymes with desired characteristics and increased enzymatic activity (Bilal et al., 2024).

3.7 Biorefinery concepts & integrated valorization

Biorefineries are integral to the transition toward a circular economy, as they facilitate the conversion of biomass and energy sources through the optimization of operational parameters across laboratory, pilot, and industrial scales. Significant progress has been made in bioenergy technologies, emphasizing the potential for enhanced process integration and innovative biomass conversion methods. These advancements aim to improve biorefinery efficiency and maximize resource utilization by transforming components such as cellulose, hemicellulose, and lignin into a diverse array of bioproducts. By reducing waste, optimizing resource use, and minimizing environmental impact, biorefineries align closely with Sustainable Development Goals (SDGs). The interdisciplinary approach combining biotechnological and thermochemical processes enables comprehensive biomass exploitation. Recent developments in genetic engineering, enzyme technology, and process optimization have played crucial roles in increasing conversion efficiencies (Meppoyilam et al., 2024).

Furthermore, optimizing energy management within biorefineries is essential not only for producing biofuels and bioproducts efficiently but also for reducing the carbon footprint of industrial activities. Lignocellulosic biomass, a complex and heterogeneous matrix composed of cellulose, hemicellulose, and lignin, varies in composition depending on the source, such as energy crops, softwoods, agricultural residues, or hardwoods. These biomasses feature a structure where cellulose is chemically bound to hemicellulose and lignin, forming lignin-carbohydrate complexes (LCCs) characterized by covalent linkages between lignin and polysaccharides.

To support industry growth, biotechnological research and development typically begin on a small scale. This foundational work is crucial for enabling the scalable expansion of biorefinery processes. Over the years, studies focusing on lignocellulosic biomass have provided valuable insights and new perspectives for industrial application. Among bioenergy and bioproducts, lignocellulosic biomass remains of significant interest for pursuing a sustainable and long-term future (Meppoyilam et al., 2024; Woiciechowski et al., 2025).

3.8. Bioactive compounds and their applications

Bioactive compounds derived from food and agro-industrial by-products are increasingly recognized for their potential to promote health beyond basic nutrition. The by-products of the vegetable oil industry represent a significant reservoir of such compounds, offering sustainable sources for the development of high-value nutraceuticals, functional foods, and pharmaceutical applications. Their recovery and utilization contribute to waste reduction, enhanced resource efficiency, and the advancement of a circular bioeconomy.

3.8.1 Polyphenols

Polyphenols comprise a diverse group of secondary plant metabolites, including phenolic acids, flavonoids, tannins, and lignans. They are abundantly present in oilseed cakes, meals, and press residues. These compounds can exist in both free and bound forms, with their concentrations influenced by processing conditions such as temperature, solvent extraction, and refining procedures. Oilseeds like sunflower, sesame, rapeseed, and olive are particularly rich sources of polyphenols. Functionally, polyphenols play a crucial role in protecting biological systems against oxidative stress through free radical scavenging and metal chelation. Beyond their antioxidant activity, they modulate cellular signaling pathways related to inflammation, apoptosis, and metabolic regulation, making them valuable ingredients in nutraceutical and pharmaceutical formulations aimed at preventing chronic diseases (Carvalho et al., 2025; Rosales & Fabi, 2023).

3.8.2 Carotenoids

Carotenoids are lipophilic pigments responsible for the yellow to red coloration of many plant-derived materials. Common carotenoids recovered from vegetable oil industry by-products include β -carotene, lutein, zeaxanthin, and lycopene, especially from palm oil residues and deodorizer distillates. Their stability and bioavailability are highly dependent on processing and formulation strategies. Biologically, carotenoids serve as potent antioxidants in lipid environments and contribute to immune modulation and cellular protection. Some carotenoids also act as precursors of vitamin A, supporting vision, skin health, and immune function. Their lipid-soluble nature makes them particularly suitable for incorporation into oil-based nutraceutical products and functional foods (Morya et al., 2022; Olivares-Tenorio et al., 2024).

3.8.3 Phytosterols

Phytosterols are naturally occurring plant sterols structurally similar to cholesterol, primarily concentrated in deodorizer distillates and soapstocks generated during oil refining. Major phytosterols include β -sitosterol, campesterol, and stigmasterol, which can be efficiently recovered through distillation and fractionation techniques. These compounds are well known for their cholesterol-lowering effects, as they compete with dietary cholesterol for absorption in the intestine. Regular intake of phytosterols has been associated with improved lipid profiles and reduced cardiovascular risk, leading to their widespread incorporation into functional foods, dietary supplements, and pharmaceutical formulations (Aboutaleb et al., 2025).

3.8.4 Dietary fibers

Dietary fibers obtained from oilseed cakes and meals consist of both soluble and insoluble polysaccharides, such as cellulose, hemicellulose, pectins, and lignin. Despite their abundance and functional potential, these fibers are often underutilized, especially in protein- and fiber-rich by-products (Azizi et al., 2018). From a health perspective, dietary fibers promote gastrointestinal health by enhancing bowel function and supporting beneficial gut microbiota. They also aid in glycemic control, cholesterol reduction, and increased satiety, making them essential components in functional foods, weight-management products, and nutraceutical formulations (Abt, 2018).

3.8.5 Tocopherols and tocotrienols

Tocopherols and tocotrienols, collectively known as vitamin E compounds, are lipid-soluble antioxidants predominantly recovered from deodorizer distillates during oil refining. These compounds differ in their side-chain saturation, which influences their biological activity and distribution within tissues. Their primary role is to protect cell membranes from oxidative damage by inhibiting lipid peroxidation. Additionally, tocopherols and tocotrienols exhibit anti-inflammatory and cardioprotective properties, supporting their use in nutraceuticals, pharmaceuticals, and cosmeceutical products (Zhang et al., 2022a).

3.9 Health-promoting and functional benefits

3.9.1 Antioxidant properties

Oxidative stress is a key factor contributing to aging and the development of chronic diseases. Bioactive compounds such as polyphenols, carotenoids, and tocopherols play a vital role in counteracting this stress by scavenging reactive oxygen species. This action helps protect lipids, proteins, and nucleic acids from oxidative damage, thereby reducing the risk of conditions such as cardiovascular diseases, cancer, and neurodegenerative disorders. Additionally, the inclusion of these bioactives in food and nutraceutical products enhances their stability and shelf life by preventing oxidative degradation (Zhang et al., 2022b).

3.9.2 Anti-inflammatory effects

Phytosterols and phenolic compounds have been shown to downregulate pro-inflammatory cytokines, offering promising therapeutic potential for managing metabolic syndrome, arthritis, and inflammatory bowel disease. Consequently, bioactive compounds derived from oil industry by-products are increasingly being explored as natural alternatives to synthetic anti-inflammatory agents (Nicolescu et al., 2023).

3.9.3 Antimicrobial properties

Certain phenolic compounds, carotenoids, and bioactive peptides exhibit antimicrobial activity against a variety of pathogenic microorganisms. These compounds can disrupt microbial cell membranes, inhibit enzyme activity, and interfere with microbial metabolic processes. Their antimicrobial properties support their use in food preservation, functional foods, and pharmaceutical applications. Moreover, natural antimicrobial bioactives meet consumer demand for clean-label products and reduce reliance on synthetic preservatives (Carvalho et al., 2025).

3.10 Potential in nutraceuticals, functional foods, and pharmaceuticals

Bioactive compounds extracted from vegetable oil industry by-products have garnered significant interest for their potential applications in nutraceuticals, owing to their proven health-promoting

properties. These compounds—including polyphenols, phytosterols, tocopherols, carotenoids, and dietary fibers—are increasingly incorporated into various nutraceutical formulations such as capsules, tablets, powders, and soft gels. They play a vital role in preventive healthcare by addressing oxidative stress, inflammation, dyslipidemia, and metabolic disorders, aligning with the rising consumer demand for natural, plant-based health supplements (Akonjuen & Aryee, 2023). Beyond their preventive benefits, nutraceuticals derived from oil industry residues offer notable advantages in terms of sustainability and cost-effectiveness. Utilizing secondary raw materials helps reduce production costs and environmental impact while facilitating the development of value-added products. Nevertheless, challenges such as compound stability, bioavailability, and standardization necessitate advanced formulation strategies and rigorous quality control to ensure consistent efficacy and regulatory compliance (Kumar et al., 2024).

Functional foods represent another prominent application area for these bioactives, integrating health benefits into everyday consumables. Ingredients like dietary fibers, phytosterols, and antioxidants are incorporated into edible oils, bakery products, dairy alternatives, beverages, and spreads to enhance their nutritional profile without compromising sensory qualities. These functional foods provide health benefits beyond basic nutrition, supporting improved gut health, cardiovascular function, and immune response. Achieving this requires careful formulation to maintain bioactive stability during processing and storage, considering factors such as heat sensitivity, oxidation, and interactions with food matrices. Advances in food processing technologies and delivery systems have facilitated the successful integration of oil-derived bioactives into diverse functional food products, promoting sustainable food innovation (Taouzin et al., 2023).

In the pharmaceutical sector, bioactive compounds from vegetable oil by-products are being explored as therapeutic agents, adjuvants, and excipients. Polyphenols and carotenoids exhibit anti-inflammatory, antimicrobial, and chemoprotective effects, while phytosterols and bioactive peptides show promise in managing cardiovascular and metabolic conditions. These compounds are often used as complementary agents alongside conventional medications to enhance therapeutic outcomes. Pharmaceutical applications demand strict quality standards, including purity, stability, and reproducibility. Although natural bioactives face regulatory and scalability challenges, advances in purification technologies and clinical validation are expanding their acceptance. Their multifunctional biological activities and favorable safety profiles position them as promising candidates for future drug development and integrative medicine approaches (Kamble et al., 2025).

3.11 Formulation and delivery systems

3.11.1 Encapsulation

Encapsulation is a widely utilized strategy for enhancing the stability and bioavailability of bioactive compounds. This technique involves enclosing active molecules within protective matrices such as polysaccharides, proteins, lipids, or biopolymers, forming micro- or nano-scale capsules (Kamble et al., 2025). Encapsulation shields sensitive bioactives from environmental factors—including light, oxygen, moisture, and temperature—that can lead to degradation. Beyond protection, this approach enables

controlled and targeted release of bioactives within the gastrointestinal tract, thereby improving absorption and biological efficacy—particularly for compounds with poor solubility or stability. Common encapsulation methods, such as spray drying, freeze drying, coacervation, and extrusion, are extensively employed in nutraceutical and pharmaceutical formulations, facilitating the development of stable and efficacious products (Chellamboli et al., 2025).

3.11.2 Nanoemulsions

Nanoemulsions are fine dispersions of oil and water phases characterized by droplet sizes typically below 200 nm. They are especially effective for delivering lipophilic bioactive compounds such as carotenoids, tocopherols, and phytosterols. Due to their small droplet size, nanoemulsions exhibit high kinetic stability and enhanced optical properties, making them suitable for use in beverages, liquid supplements, and pharmaceutical formulations (Tripathy et al., 2023). The increased surface area of nanoemulsions significantly improves the solubility, digestion, and intestinal absorption of bioactives, resulting in higher bioavailability. Moreover, nanoemulsions can be engineered for controlled release and targeted delivery. Their versatility and efficiency position them as a key technology in the development of modern nutraceuticals and functional foods, although challenges related to scalability and regulatory approval remain (Kumar et al., 2024; Siraj et al., 2021).

3.11.3 Bioactive-enriched ingredients

Bioactive-enriched ingredients are concentrated fractions obtained through selective extraction, purification, or biorefinery processes. These ingredients contain high concentrations of specific bioactive compounds and can be directly incorporated into food, nutraceutical, or pharmaceutical formulations. Examples include polyphenol-rich extracts, fiber-enriched flours, and phytosterol-fortified oil fractions (Djebbar et al., 2024). The use of bioactive-enriched ingredients simplifies formulation processes, ensures consistent dosing, and enhances functionality. Additionally, they support clean-label product development by reducing the need for synthetic additives. From a sustainability perspective, these ingredients offer an efficient means of valorising vegetable oil industry by-products, transforming low-value residues into high-value functional components that contribute to the principles of a circular bioeconomy (Akonjue & Aryee, 2023).

3.12 Successful valorization examples

3.12.1 Conversion of seed cakes into nutraceuticals

Oilseed cakes, the by-products obtained after oil extraction from seeds, possess a diverse and valuable composition that varies depending on the extraction method employed—such as mechanical pressing, solvent extraction, cold pressing, or supercritical CO₂ extraction. Despite their rich nutritional profile, these cakes are often underutilized, representing a promising resource for sustainable applications in the food and pharmaceutical industries. This section explores various valorization strategies emphasizing their high protein content (up to 56%) and fiber content (up to 66%). Both traditional and innovative extraction techniques are highlighted, including ultrasound-assisted extraction (achieving up

to 96.64% phenolic compound yield), enzymatic methods (with 82–83% protein recovery), and subcritical water extraction, all of which enhance efficiency while minimizing environmental impact. Oilseed cakes have versatile applications, ranging from gluten-free bakery products and plant-based meat alternatives to advanced nanoencapsulation systems for bioactive compounds. Notably, major oilseed varieties such as soybean, rapeseed, sunflower, and flaxseed exhibit unique nutritional and functional properties that can be optimized through appropriate processing techniques (Švarc-Gajić et al., 2020). The high protein content and variable nutritional profiles—regulated by agronomic, processing, and genetic factors—underscore the importance of understanding these by-products for effective valorization. Future research is focused on integrating green technologies such as pulsed electric field (PEF) and high hydrostatic pressure (HHP) at an industrial scale, developing comprehensive biorefinery approaches, and further exploring the health benefits of oilseed-derived peptides and fibers to enhance consumer acceptance and regulatory approval (Grahovac et al., 2025).

3.12.2 Extraction of antioxidants for nutraceuticals, cosmeceuticals, pharmaceuticals, and food industries

An innovative example of valorization involves the utilization of pomegranate (*Punica granatum*) waste through green solvent extraction and biochar production. This approach exemplifies a sustainable, zero-waste biorefinery model that maximizes biomass utilization while adhering to principles of green chemistry. The process involves sequential extraction of valuable bioactives—such as anthocyanins and ellagic acid derivatives—using environmentally friendly solvents, followed by the transformation of residual biomass into high-efficiency biochar. Quantitative sustainability assessments, such as a Path2Green score of 0.401 (equivalent to approximately 288.50 g CO₂ per gram of biomass), demonstrate the environmental benefits of this process. The approach not only eliminates waste streams but also replaces hazardous organic solvents with bio-based alternatives, fostering environmentally sustainable industrial practices. The biorefinery technique employs multiproduct extraction strategies, with gamma-valerolactone (GVL) enhancing anthocyanin extraction and [Ch][OAc] facilitating ellagic acid recovery from residues (Maggiore & Setti, 2025). The extracted bioactive compounds have diverse commercial applications, including natural colorants in food and active ingredients in nutraceutical, cosmeceutical, and pharmaceutical products. The residual biomass is further converted into a highly effective absorbent biochar using milder conditions and [Ch]Cl:OA, which demonstrates excellent adsorption capacity for synthetic dyes, offering a promising solution for wastewater remediation. The sustainability and environmental impact of this biorefinery process were rigorously evaluated using the 12 principles of green extraction, confirming its high efficiency with a Path2Green score of 0.401. This innovative technique underscores the potential of alternative, bio-based solvents to reduce waste, lower environmental impact, and promote greener industrial practices—marking significant progress in sustainable biorefinery technologies. The study also emphasizes the crucial role of non-conventional solvents, providing valuable insights into their industrial feasibility and broader applications (de Souza Mesquita et al., 2024; Mia et al., 2025).

3.13 Sustainable biorefinery models

The rapid pace of global urbanization has led to a significant increase in energy and material consumption, accompanied by the generation of anthropogenic waste. Currently, petroleum refineries serve as the primary source meeting these demands, but their extensive use exerts considerable pressure on the energy-environment nexus. Thereby, the production of bioenergy and biomaterials offers a promising alternative to address the escalating global needs. The biorefinery concept challenges traditional waste disposal by reimagining low-value or negative-value waste streams as renewable feedstocks for sustainable energy and material production (Venkata Mohan et al., 2016).

Biorefineries have emerged as a sustainable platform for converting biomass into a diverse array of products, thus supporting the circular bioeconomy paradigm (Fig. 3). This approach emphasizes the efficient and sustainable valorization of biomass, fostering resource regeneration and restorative production systems. Specifically, biowaste biorefinery, depicted in Fig. 4, has proven to be a sustainable strategy for producing integrated bioproducts, with applications spanning industrial, commercial, agricultural, and energy sectors. Grounded in the principles of carbon-neutral development, this review provides a comprehensive overview of biowaste as a renewable resource, highlighting technologies for energy, nutrient, and material recovery within the biorefinery framework. The success of biorefinery technologies depends on their environmental sustainability, economic viability, technical feasibility, social acceptance, and supportive policy frameworks. Advancing sustainable biorefinery approaches toward a circular bioeconomy requires a holistic understanding of biowaste generation and collection across the entire value chain.

Building on the concept of carbon-neutral biowaste biorefinery, this review discusses how biowaste generation and utilization can serve as renewable resources through innovative biorefinery techniques focused on energy, nutrient, and material recovery (Duan et al., 2022). Biorefineries offer a sustainable alternative to petrochemical industries by utilizing waste streams to produce a broad spectrum of marketable bioproducts and bioenergy. Valorization of waste or side streams into bioprocesses for producing value-added bioproducts, such as biopolymers and bio-lipids, significantly advocates for a sustainable circular bioeconomy. The integration of waste biorefinery approaches with circular economy principles holds considerable promise for achieving sustainability and warrants accelerated development through supportive policies, investment, and technological innovation (Duan et al., 2022; Leong et al., 2021).

3.14 Circular bioeconomy initiatives

The escalating challenge of food waste management not only poses an urgent environmental problem but also presents a significant opportunity to advance the circular bioeconomy. Transforming food waste from a disposal burden into a valuable resource (Fig. 5) enables the development of sustainable systems that mitigate environmental impacts while generating economic benefits. Innovative strategies that integrate sustainable technologies and zero-waste principles are paving the way toward closed-loop food systems. These systems enhance resource efficiency, reduce ecological footprints, and bolster food security by converting food waste into renewable food resources. The adoption of circular

bioeconomy models as comprehensive frameworks allows for the simultaneous addressing of multiple sustainability dimensions. Instead of viewing waste management, economic growth, and environmental protection as competing priorities requiring trade-offs, circular bioeconomy approaches—exemplified through food waste valorization—facilitate synergistic solutions. These solutions promote waste reduction, drive economic value creation, and support the sustainable fulfilment of future food demands (Pal et al., 2024).

The production of potato starch-based biomaterials aligns strongly with the European Union's comprehensive sustainability framework and legislative architecture supporting the transition to a circular economy. Valorization of potato starch is consistent with the Waste Framework Directive, which emphasizes the recovery and reuse of organic materials. This approach promotes the development of alternatives to fossil-based products, enhances the sustainability performance of agricultural value chains, and enables competitive pricing through efficient resource utilization. Such an integrated strategy advances ambitious environmental targets set at the European level while creating new economic opportunities within the bioeconomy sector. The success of this bioeconomy model and the proposed potato starch valorization scheme fundamentally depends on active collaboration between primary producers (farmers) and agro-industrial processors. This partnership is crucial for ensuring a consistent supply of feedstock, validating product performance under real-world agricultural conditions, optimizing logistics and costs, and fostering market acceptance. By involving farmers as both suppliers and end-users, aligned incentives and shared value are established, strengthening the viability and scalability of circular bioeconomy initiatives in agriculture.

A case study exemplifying circular bioeconomy principles is the food waste valorization through composting systems of restaurant organic waste. Local composting can effectively reduce organic waste collected from foodservice establishments, offering environmental and economic benefits. When operated under optimal conditions, such systems contribute to zero-emission transportation of food waste and produce mature compost that can serve as organic fertilizer for green spaces, such as parking lot landscaping (Feodorov et al., 2022).

Growing environmental concerns and the urgent need to mitigate the impacts of conventional plastics have fuelled extensive research into biodegradable materials and the valorization of agro-industrial waste streams. Significant progress has been made in replacing traditional plastics with biodegradable alternatives, such as polylactic acid (PLA), produced from fermented plant sugars. Additionally, starch-based biopolymers derived from crops like potato, corn, wheat, or cassava are increasingly utilized in creating functional films and packaging materials, including those made from marine by-products and fishery industry waste, fostering active packaging solutions and adding value to previously underutilized resources. Microalgal biomass has also been explored for biopolymer production, offering a promising alternative to fossil-based materials. Among plant-derived sources, by-products from cereal and citrus fruit processing are notable due to their rich content of bioactive compounds with desirable properties for biodegradable packaging. For example, grape pomace, an underused by-product, has high potential for industrial reuse. The conversion of jackfruit into value-added polymers further exemplifies the

potential for developing sustainable materials. Collectively, these diverse studies demonstrate the feasibility of producing biodegradable materials while creating economic opportunities across various sectors (Oliveira et al., 2025).

3.15 Challenges

3.15.1 Technical and economic challenges

3.15.1.1 Scalability and Process Optimization

Translating valorization techniques for vegetable oil by-products from laboratory and pilot-scale settings to large-scale industrial operations remains a significant hurdle. Although advanced extraction and bioconversion methods—such as supercritical fluid extraction, enzymatic treatments, and membrane separation—demonstrate high efficiency at smaller scales, their performance often diminishes during scale-up due to increased energy demands, mass transfer limitations, and complex equipment requirements. Ensuring consistent quality and bioactivity of recovered compounds across large production volumes is particularly challenging, especially when raw material composition varies with crop type, seasonal fluctuations, and processing conditions (Nemli et al., 2025d). Consequently, process optimization becomes essential for achieving stable, reproducible operations with high recovery yields. This entails meticulous adjustment of operational parameters like temperature, pressure, solvent ratios, enzyme concentrations, and processing durations, while simultaneously minimizing energy and water consumption. Incorporating digital technologies—including process simulation, artificial intelligence, and real-time monitoring—is increasingly recognized as an effective strategy to enhance scalability and operational control. Additionally, integrated biorefinery configurations that enable the simultaneous extraction of multiple bioactive compounds can substantially improve overall efficiency and industrial feasibility (Dai & Mumper, 2010; Menghini et al., 2018).

3.15.1.2 Cost-effectiveness and market acceptance

The economic viability of bioactive products derived from vegetable oil industry by-products is a critical factor influencing their successful commercialization. High initial investments, along with ongoing operational and maintenance costs associated with environmentally friendly extraction technologies, often limit adoption—particularly among small and medium enterprises. Furthermore, expenses related to purification, product formulation, quality assurance, and regulatory compliance can significantly inflate final product costs, reducing their competitiveness against synthetic alternatives (Brown et al., 2012). Consumer and industry acceptance also pose substantial barriers, especially in food, nutraceutical, and pharmaceutical markets where strict standards for quality, safety, and efficacy are enforced. The perception that ingredients sourced from industrial residues are inferior or potentially unsafe can hinder market penetration, even when scientific evidence supports their health benefits (Fernandes et al., 2025). Addressing these challenges requires transparent labelling, rigorous validation, clinical evidence, and

consumer education initiatives. Collaboration among industry, academia, and regulatory bodies can further help reduce costs and improve market readiness (Liguori & Faraco, 2016).

3.15.2 Environmental and regulatory considerations

3.15.2.1 Sustainability assessments

While valorising vegetable oil by-products inherently aligns with sustainability goals, comprehensive environmental evaluations are necessary to verify actual ecological benefits. Life cycle assessment (LCA) methodologies are essential for quantifying impacts related to energy consumption, greenhouse gas emissions, water use, and waste generation throughout the entire valorization process (Cherubini et al., 2009). Certain energy-intensive steps may offset environmental gains if not properly optimized. Incorporating sustainability assessments during process development allows researchers and industry stakeholders to identify environmental bottlenecks and enhance resource efficiency (ISO 14040:2006, 2022; Rodríguez-Pérez et al., 2025). Strategies such as adopting renewable energy sources, water recycling, and eco-friendly solvents can further improve environmental performance. Increasingly, sustainability metrics serve as vital decision-making tools for policymakers, investors, and industry leaders committed to environmentally responsible innovations within the circular bioeconomy framework (Hoek et al., 2021).

3.15.2.2 Food-grade and safety regulations

Regulatory compliance remains one of the most significant challenges in utilizing vegetable oil by-products for bioactive applications. Ingredients intended for food, nutraceutical, cosmetic, or pharmaceutical use must meet stringent safety and quality standards established by agencies like EFSA, FDA, and corresponding national authorities. Rigorous evaluation of solvent residues, contaminants, allergens, and toxicological risks is required through standardized testing protocols. Moreover, regulatory pathways for ingredients derived from industrial residues are often poorly defined, resulting in lengthy approval processes that delay market entry. Developing harmonized international regulations and specific guidelines for bioactive compounds from agro-industrial by-products is crucial. Clear regulatory frameworks can foster industry investment, accelerate innovation, and ensure consumer safety, thereby supporting the growth of the circular bioeconomy (EFSA, 2012; European Union, 2013; FDA, 2017).

3.16 Future directions

3.16.1 Integration of multi-valorization processes

Future research and industrial applications are expected to focus on integrated multi-valorization strategies, wherein multiple valuable components are extracted from a single by-product stream. Instead of targeting a single compound, next-generation biorefineries aim to sequentially recover proteins, polyphenols, dietary fibers, lipids, and energy-dense fractions to maximize resource utilization and economic return. Such integrated approaches reduce waste generation and enhance overall process efficiency, thereby advancing sustainability and commercial viability (Kamm & Kamm, 2004; Morales-

Polo et al., 2019). Designing flexible, modular processing systems capable of handling diverse raw materials—characterized by variable composition—is particularly vital for vegetable oil industries. Combining physical, chemical, and biological techniques in a unified platform can significantly boost productivity while lowering environmental impact, shaping the future landscape of sustainable agro-industrial biorefineries (Kumar et al., 2025; Otles & Kartal, 2018).

3.16.2 Policy support for circular bioeconomy

Strong policy frameworks are essential to accelerate the deployment of valorization technologies and promote circular bioeconomic practices. Incentives such as tax exemptions, subsidies, research grants, and public-private partnerships can mitigate financial risks associated with innovative processes. Policies emphasizing waste reduction, efficient resource use, and sustainable manufacturing can facilitate the transition from linear to circular models. Additionally, integrating agro-industrial by-product valorization into national bioeconomy strategies can foster industry collaboration and regional economic development. Clear regulatory guidance, unified sustainability standards, and international cooperation are critical to creating a conducive environment for innovation. Market demand driven by sustainability policies will further stimulate industrial growth and product diversification (EFSA, 2017; Geissdoerfer et al., 2017).

3.16.3 Interdisciplinary research and innovation

Realizing the full potential of vegetable oil by-product valorization necessitates collaborative efforts across multiple disciplines—including food science, chemical engineering, biotechnology, environmental science, economics, and regulatory affairs (Baky et al., 2025). This interdisciplinary approach facilitates the development of efficient extraction methods, environmentally sustainable technologies, and market-ready bioactive products. It also supports the translation of laboratory discoveries into scalable industrial solutions. Emerging innovations—such as nano-delivery systems, computational modelling, and bioinformatics screening—offer promising avenues to improve stability, bioavailability, and efficacy of recovered compounds. Partnerships between academia and industry, underpinned by open innovation models, will be pivotal in overcoming current limitations and advancing sustainable valorization technologies (Herrero et al., 2015; Kyriakoudi et al., 2021).

3.17 Novelty impact statement

This systematic review emphasizes the transformative potential of novel valorization pathways for vegetable oil industry by-products, highlighting their critical role in advancing sustainable bioeconomy principles. By integrating state-of-the-art green extraction technologies—such as supercritical fluid extraction, enzyme-assisted extraction, and pressurized liquid extraction—this study demonstrates how low-value residues can be converted into high-value bioactive compounds with diverse health-promoting properties. The innovation lies in combining these recent technological advances to enhance recovery efficiency while minimizing environmental impact, thereby supporting circular economy models within the vegetable oil sector. Deliberate valorization of these by-products not only reduces industrial waste and greenhouse gas emissions but also stimulates the development of functional foods, nutraceuticals,

and pharmaceuticals—effectively linking environmental sustainability with economic growth and technological innovation.

3.18 Alignment with UN Sustainable Development Goals (SDGs)

This study strongly aligns with several UN SDGs, including SDG 12 (Responsible Consumption and Production), SDG 13 (Climate Action), and SDG 3 (Good Health and Well-Being). It promotes responsible resource management and waste reduction by enhancing the long-term utilization and value of vegetable oil by-products, thereby contributing directly to SDG 12. The adoption of environmentally friendly extraction and biorefinery technologies supports climate action by reducing carbon footprints and fostering renewable energy and bioproducts, in accordance with SDG 13. Additionally, the development of bioactive compounds with health benefits directly advances SDG 3, which aims to improve human health through natural, safe, and functional ingredients. Overall, this work advocates for a comprehensive approach that combines technological innovation, environmental responsibility, and health promotion to accelerate the transition toward a resilient and sustainable circular bioeconomy.

4 Conclusions

The innovative utilization of by-products from the vegetable oil industry marks a significant advancement in sustainable resource management within the framework of the circular bioeconomy. Converting underutilized residues into valuable bioactive ingredients not only alleviates environmental concerns but also opens new avenues for economic growth. Advances in green extraction techniques, integrated biorefinery systems, and interdisciplinary research have underscored the immense potential of these by-products for applications across the food, nutraceutical, pharmaceutical, and cosmetic industries. Implementing effective valorization strategies can substantially reduce industrial waste, lower carbon emissions, and decrease dependence on synthetic materials, thereby supporting long-term sustainability goals. With ongoing technological improvements, supportive policy initiatives, and clear regulatory frameworks, the vegetable oil sector can play a pivotal role in developing a resilient and sustainable bio-based economy. Ultimately, these innovative valorization approaches offer far-reaching benefits beyond industry, promoting public health, environmental preservation, and socio-economic development.

Abbreviations

AA	
antioxidant activity	
AFW	
agro-food waste	
APIs	
active pharmaceutical ingredients	
EAE	

enzyme-assisted extraction
GVL
gamma-valerolactone
HHP
high hydrostatic pressure
LCCs
lignin-carbohydrate complexes
MWAE
microwave-assisted extraction
PEF
pulsed electric fields
PHW
pressurized hot water
PLE
pressurized liquid extraction
PRISMA
Preferred Reporting Items for Systematic reviews and Meta-Analyses
SDGs
sustainable development goals
SFE
supercritical fluid extraction
TP
total polyphenols
UAE
ultrasound-assisted extraction
UN
United Nations

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Data availability

The authors confirm that the data supporting the findings of this study are available within the article.

Clinical trial number

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Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

The authors declare that they have no competing interests.

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Figures

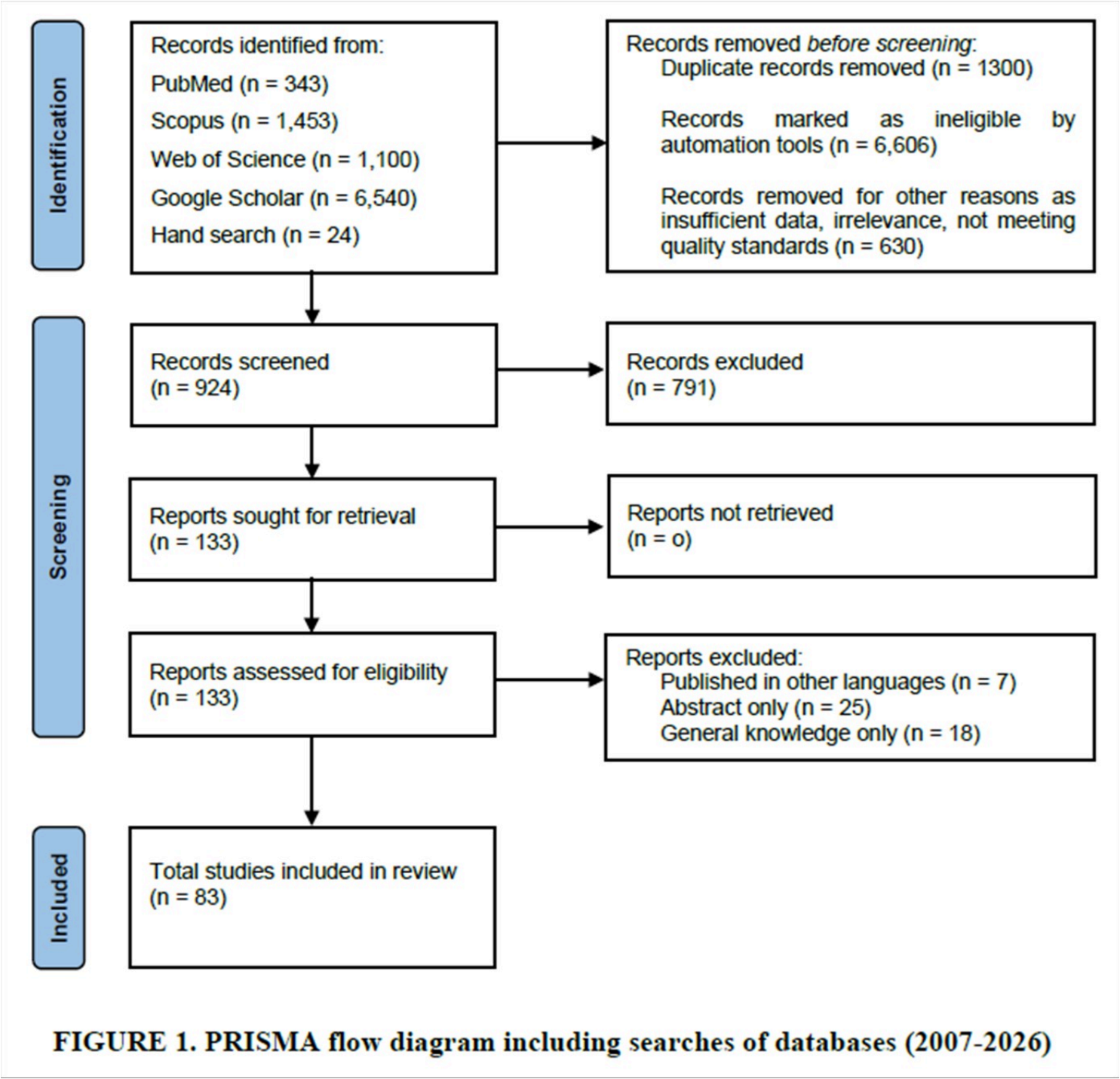


Figure 1

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FIGURE 2. Experimental design of innovative valorization of vegetable oil industry by-products for bioactive resources in sustainable circular bioeconomy

Figure 2

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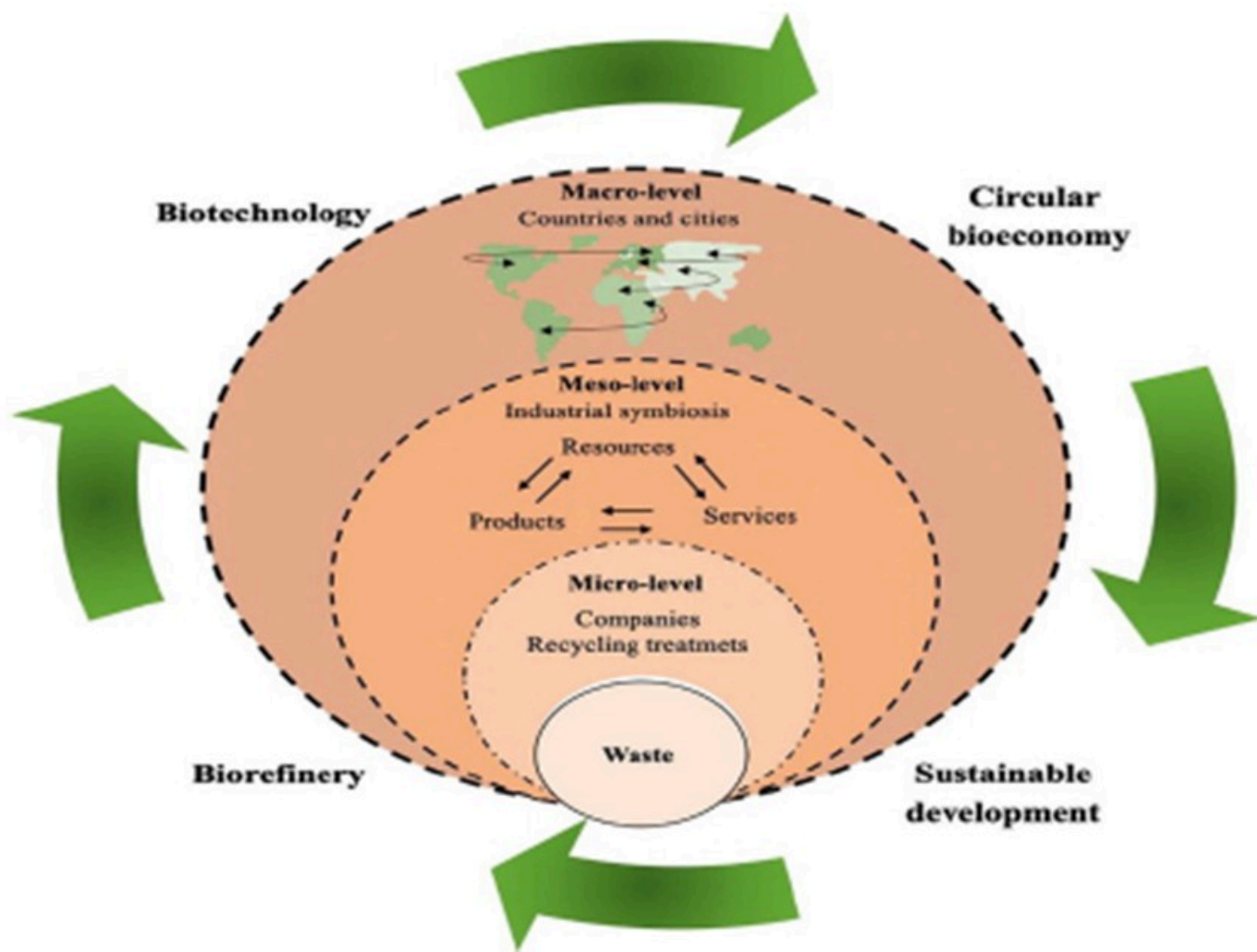


FIGURE 3. Sustainable biorefinery models

Figure 3

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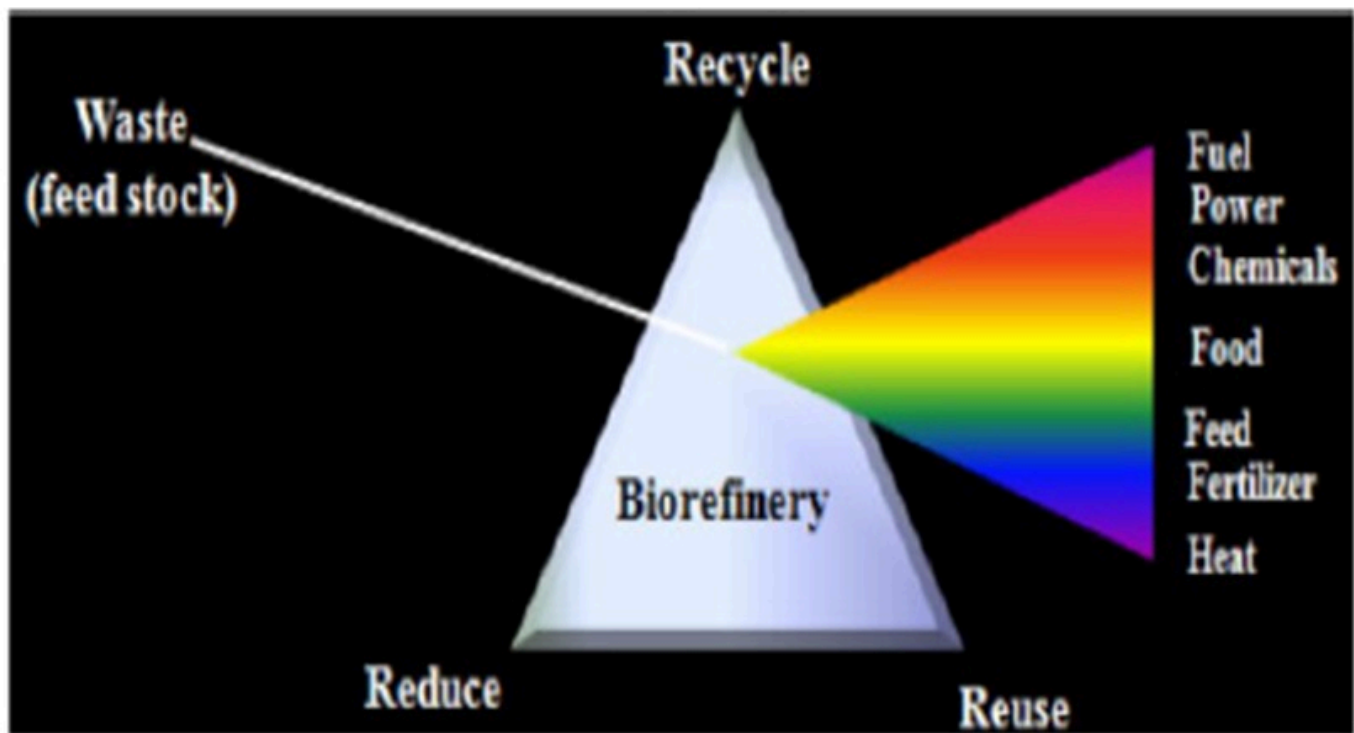


FIGURE 4. Sustainable biowaste biorefinery models

Figure 4

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FIGURE 5. Circular bioeconomy initiatives

Figure 5

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