Review

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The Valorization of Agrifood Byproducts and Waste to Advance the Sustainable Development Goals: Current State and New Perspectives

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Abstract

Approximately a third (1.3 billion tons) of the food that is generated globally is lost each year, and it accounts for over 20% of the global greenhouse gas emissions. Most of this loss is by-products generated during post-harvest and food processing, which account for 30–50% of raw materials, including shells, skins, pulp, stems, and seeds. While generally wasted, such by-products contain precious bioactive molecules such as phenolic acids, bioactive peptides, carotenoids, fibers, and secondary metabolites (e.g., terpenes, polyphenols, alkaloids) and minerals, amino acids, and vitamins. This review outlines how these high value agrifood by-products can be utilized towards achieving sustainable development goals (SDGs). It encompasses extraction methods, characterization, and potential uses of such active compounds in the food, pharmaceutical, packaging, and cosmetic sectors. Moreover, it examines the interaction between valuing agrifood by-products and key SDGs like eliminating hunger (SDG 2), ensuring good health and well-being (SDG 3), promoting affordable and clean energy (SDG 7), promoting economic growth and decent work (SDG 8), ensuring responsible consumption and production (SDG 12), and tackling climate action (SDG 13). These approaches have high potential to improve food security and economic sustainability of the world's food systems.

Keywords: agrifood by-products; waste; sustainability; active ingredients; sustainable development goals; circular bioeconomy

1. Introduction

The agri-food sector is among the most expansive and economically influential industries worldwide, playing a pivotal role in guaranteeing food supply, promoting nutritional well-being, and driving socio-economic advancement [1,2]. This industry comprises a broad spectrum of interconnected activities, ranging from primary agricultural production to food processing, distribution, and retail. It employed nearly 1.3 billion people in 2021, representing 39.2% of the global workforce, and contributes substantially to both national and global economies [3–5]. Nonetheless, despite its indispensable functions, the agri-food sector is also a major source of organic waste and by-products, which raises considerable environmental, financial, and logistical concerns [6]. The global value of food lost or wasted is estimated to reach US$1 trillion, representing a significant economic and resource inefficiency [7]. Furthermore, both developed and developing nations contribute almost equally to this challenge, despite vast differences in population size and consumption patterns. Developed countries, with a population of approximately 1.4 billion, are responsible for discarding about 670 million tons of edible food, largely driven by consumer behavior and retail practices. In contrast, developing countries, home to 6.2 billion people, waste around 630 million tons, primarily due to inadequate storage, transportation, and processing infrastructure [8,9]. Environmentally, food waste is a significant contributor to climate change, with an estimated 1.3 billion tons of food wasted each year. This represents 30% of the total food produced for human consumption and accounts for 8–10% of global greenhouse gas emissions linked to food waste [10,11].

By-products are generated throughout the different stages of the food supply chain and encompass a wide variety of materials [12], including plant residues (peels, pulps, seeds, husks, stems, leaves) [13], animal-derived wastes (whey, bran) [14], processing residues (oilseed cakes, pomace) [15], and wastewater from operations like washing, blanching, pressing, and extraction [16]. The volume and chemical composition of these residues vary depending on factors such as the type of raw material, the technological processes applied, and regional agricultural conditions [17,18]. Traditionally, these materials have been considered low-value waste, typically disposed of via landfilling [19], incineration [17], or use as animal feed [20], practices that often result in inefficient resource utilization and negative environmental impacts [21] (Figure 1).

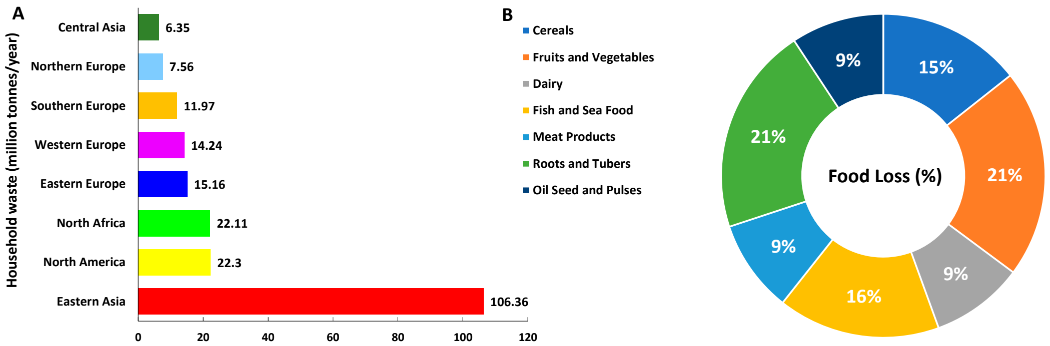

Figure 1. (A) Household food waste in selected regions (million tons per year) [22]. (B) Global distribution of food waste by category (%), with fruits and vegetables as the major contributors, followed by roots and tubers, fish and seafood, cereals, dairy, meat, and oilseeds and pulses.

Recently, however, a notable transformation has occurred in how these agri-food residues are viewed [23]. With the emergence of green technologies, advancements in bioprocessing, and progress in environmental biotechnology, these by-products are now increasingly identified as sustainable, low-cost raw materials, rich in valuable bioactive constituents [6,24,25]. These include phenolic compounds, flavonoids, antioxidants, essential fatty acids, dietary fibers, fermentable carbohydrates, amino acids, and functional proteins [26,27]. This shift in perspective paves the way for the development of innovative valorization pathways, enabling the conversion of these materials into high-value products applicable across multiple sectors, including food, pharmaceutical, cosmetic, energy, and agricultural industries. As a result, agri-food by-product valorization is increasingly recognized as a key strategy in advancing sustainability, minimizing waste disposal, and generating value-added products, thereby contributing to the development of sustainable and circular food systems [28,29].

The valorization of agri-food by-products offers a substantial opportunity to move away from conventional linear food production systems, characterized by a take-make-dispose model, towards circular and sustainable frameworks [30,31]. This transition not only reduces environmental burdens but also maximizes resource efficiency and aligns strongly with the global agenda defined by the United Nations Sustainable Development Goals (SDGs) [32]. The transformation of agri-food waste into high-value resources positions by-product valorization as a pivotal mechanism for advancing several interlinked SDGs, thereby contributing to the establishment of a more equitable, resilient, and resource-efficient society [33].

The valorization of agri-food by-products plays a pivotal role in advancing multiple interrelated SDGs. It contributes to SDG 2 (Zero Hunger) by transforming organic waste into valuable food ingredients, fertilizers, and animal feed, thereby improving food availability and nutrition, particularly in low-resource areas [34]. For SDG 7 (Affordable and Clean Energy), agri-food residues serve as effective feedstocks for renewable energy production such as biogas, bioethanol, and green hydrogen through sustainable biochemical and thermochemical processes [30,35]. In relation to SDG 9 (Industry, Innovation, and Infrastructure), innovative biotechnological applications are driving the development of green industrial models and infrastructure for efficient waste transformation [36]. Through SDG 12 (Responsible Consumption and Production), these strategies close material loops, reduce waste, and promote sustainable use of natural resources [35]. Finally, in support of SDG 13 (Climate Action), the diversion of organic waste from landfills helps reduce greenhouse gas emissions, while carbon-neutral and carbon-negative processes enhance climate mitigation efforts [37]. Collectively, these contributions position by-product valorization as a cornerstone in building sustainable, resilient, and resource-efficient food systems [33].

Recent advancements in biorefinery frameworks, green chemistry principles, and microbial biotechnology have fundamentally transformed the treatment and utilization of agri-food by-products [13,25]. Advanced technologies now enable the efficient extraction of valuable bioactive compounds such as polyphenols, carotenoids, and prebiotics from agri-food by-products. Owing to their health and functional benefits, these compounds are in high demand across sectors like food, pharmaceuticals, cosmetics, and bioenergy, thereby reinforcing the importance of sustainable by-product valorization [38,39].

Although significant technological progress has been made and the advantages of agri-food by-product valorization are increasingly well-documented, its large-scale industrial implementation still faces multiple barriers [28,30]. These include inconsistencies in by-product composition, disjointed supply chains, high operational and investment costs, complex regulatory frameworks, and a lack of widespread consumer acceptance. Addressing these challenges demands a multidisciplinary and integrated strategy that combines scientific research with economic planning and effective policymaking. Promoting collaborative efforts, establishing enabling regulatory environments, offering financial support mechanisms, and raising public awareness are all vital to advancing the shift toward circular, sustainable, and resilient agri-food systems [6,28,38].

This review aims to present a comprehensive and critical overview of the current state of agri-food by-product valorization, emphasizing its potential as a strategic pathway toward sustainable development. It explores the bioactive compounds commonly found in agri-food residues and examines the advanced methods employed for their efficient recovery and utilization. The study also investigates the environmental and economic benefits associated with these practices and analyzes their relevance to the broader framework of the United Nations Sustainable Development Goals (SDGs). Additionally, it addresses the key challenges and limitations that continue to hinder large-scale industrial adoption, including technological, economic, and regulatory barriers. Considering emerging innovations such as digitalization, artificial intelligence, and precision fermentation, the review highlights new perspectives that can drive the sustainable transformation of agri-food systems. Ultimately, it advocates for a shift in perception, recognizing agri-food by-products not as waste, but as valuable resources at the heart of resilient and circular bio-economies.

2. Active Ingredients in Agri-Food by-Products

Agri-food by-products, which were once dismissed as low-value waste, are now increasingly recognized for their richness in high-value bioactive compounds that hold considerable importance across various industrial sectors [40]. These by-products originating from the processing of fruits, vegetables, cereals, oilseeds, and other agricultural materials are produced in large quantities and have traditionally been discarded or underexploited. However, under the principles of a circular bioeconomy, they are now viewed as promising raw materials for extracting biologically active substances [23].

These compounds often termed functional ingredients or bioactive constituents include a wide range of molecules such as polyphenols, carotenoids, dietary fibers, bioactive lipids, peptides, and phytochemicals [27]. They are known for their diverse health-related and functional effects, including antioxidant [41], anti-inflammatory, antimicrobial, cholesterol-lowering, immune-boosting, and anticancer properties [42,43]. Additionally, many of these molecules offer technological benefits, enhancing the physical and chemical stability of food and cosmetic products [44].

Given these versatile attributes, the valorization of agri-food by-products has emerged as a key strategy for sustainable innovation. In the food and nutrition sector, these compounds are incorporated into functional foods and nutraceuticals aimed at promoting health and preventing disease [23,45]. They are also utilized in the livestock sector as animal feed [46]. In the pharmaceutical field, they are being investigated as potential therapeutic agents or complementary bio actives in drug development. The cosmetic industry also capitalizes on these natural ingredients for their bioactive properties in skincare and personal care products [29]. Furthermore, in the renewable energy domain, lipid- or carbohydrate-rich residues are utilized in the production of biofuels such as biogas, biodiesel, and bioethanol, supporting the transition to cleaner energy sources [47].

This evolving perspective from waste disposal to resource recovery emphasizes the importance of sustainable biorefinery processes and environmentally friendly extraction technologies. It also highlights the role of bioactive recovery in enhancing resource efficiency, minimizing ecological impact, and fostering economic sustainability through circular agri-food systems [17,30].

Figure 2 illustrates the valorization pathways of plant by-products. Extracts and hydrolates obtained from these materials are utilized in diverse sectors, including biofuels, animal feed, biopesticides, food and pharmaceutical industries, and soil and water remediation, highlighting a circular and sustainable bioeconomy approach.

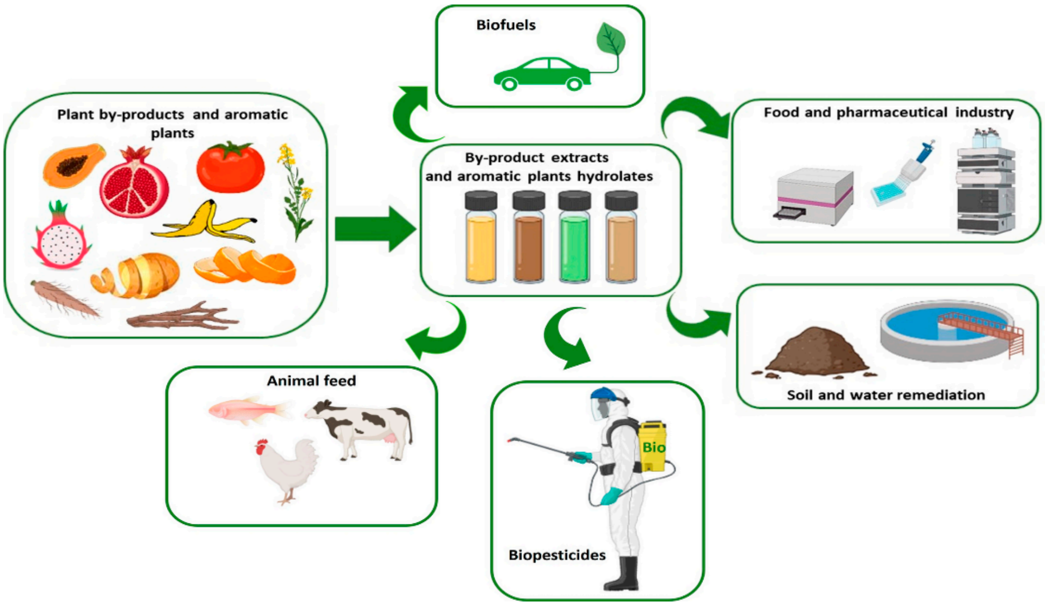

Figure 2. Valorization of plant-derived by-products for applications in food, pharmaceutical, and environmental remediation sectors [48].

2.1. Polyphenols

Polyphenols represent a highly diverse class of secondary metabolites, broadly categorized into major subclasses including flavonoids, phenolic acids, tannins, and stilbenes [49]. These compounds are biosynthesized by plants as part of their adaptative response to various environmental stresses, playing a critical role in defense mechanisms against pathogens, ultraviolet radiation, and oxidative damage. They are predominantly concentrated in the peels of fruits, vegetable residues from agro-industrial processes, cereal husks, and notably within olive mill wastes, where their accumulation is significant [48]. The biological activities of polyphenols encompass potent antioxidant properties, which enable the scavenging of reactive oxygen species and the protection of cellular components from oxidative stress [38]. Additionally, they exhibit anti-inflammatory effects through the modulation of key cellular signaling pathways. Moreover, polyphenols demonstrate antimicrobial efficacy against a range of pathogenic microorganisms and possess anticancer potential by inducing apoptosis and inhibiting tumor cell proliferation, thereby representing promising agents for both preventive and therapeutic applications in human health [50].

Among agro-food by-products, specific matrices such as apple peels, grape skins, and olive leaves are particularly enriched with phenolic compounds including quercetin, gallic acid, and hydroxytyrosol, which are well recognized for their bioavailability and robust antioxidant capacities [51]. These phenolics can be effectively extracted and valorized for innovative formulations, thereby supporting circular economic initiatives and waste minimization strategies. Furthermore, olive mill wastewater (OMW) constitutes a concentrated source of water-soluble phenolic compounds, whose complex polyphenolic profile confers pronounced bioactivity. Extracts derived from OMW have demonstrated substantial potential for incorporation into the development of nutraceuticals and functional foods, with emerging applications also in the cosmeceutical sector due to their antioxidant and anti-aging properties [41,52]. The valorization of these effluents not only contributes to environmental protection by mitigating pollution but also fosters innovation within the health and wellness industries [52].

2.2. Carotenoids

Carotenoids constitute a class of naturally occurring lipid-soluble pigments responsible for the characteristic red, yellow, and orange coloration of numerous fruits and vegetables. These tetraterpenoid compounds are synthesized via the isoprenoid biosynthetic pathway and serve vital functions in plants, including photoprotection and antioxidative defense [53]. Agri-food residues from carrots, tomatoes, citrus peels, and pumpkins represent particularly rich and sustainable sources of key carotenoids such as β-carotene, lycopene, lutein, and zeaxanthin. These compounds exhibit notable antioxidant properties through the quenching of singlet oxygen and scavenging of free radicals, thereby mitigating oxidative stress implicated in the development of chronic diseases [49].

Epidemiological and clinical evidence has linked increased carotenoid intake with reduced risks of cardiovascular diseases, by improving endothelial function and reducing systemic inflammation. In addition, carotenoids like lutein and zeaxanthin selectively accumulate in the macula lutea of the human retina, where they contribute to protection against age-related macular degeneration by filtering harmful blue light and reducing oxidative damage to retinal cells [53]. Furthermore, several studies have suggested an inverse association between carotenoid levels and the risk of certain cancers, including prostate and breast cancers, attributed to their ability to modulate cell proliferation, apoptosis, and immune responses [54].

Due to their lipophilic nature, carotenoids require incorporation into lipid-based delivery systems to improve their bioavailability and stability. Novel encapsulation technologies such as nano emulsions, liposomes, and solid lipid nanoparticles have been developed to protect carotenoids from degradation and enhance their controlled release in food and pharmaceutical applications [49]. The valorization of carotenoid-rich agri-food by-products not only contributes to sustainable waste management but also provides valuable bioactive ingredients for functional foods, nutraceuticals, and cosmetics industries [6].

2.3. Dietary Fibers

Dietary fibers, comprising both soluble fractions such as pectins, gums, and inulin, and insoluble fractions including cellulose, hemicellulose, and lignin, are predominantly abundant in agri-food by-products such as cereal bran, fruit pomace, and oilseed cakes [55]. These fibers serve multifaceted roles in food technology, acting as thickeners, gelling agents, stabilizers, and texture enhancers, thereby improving the mechanical and rheological properties of diverse food matrices [23]. Beyond their technological applications, dietary fibers exert significant physiological benefits. Soluble fibers slow gastric emptying and modulate glucose absorption, leading to attenuated postprandial glycemic excursions, which is critical for metabolic health and diabetes management. Additionally, both soluble and insoluble fibers contribute to lipid metabolism regulation by enhancing bile acid excretion and reducing serum cholesterol levels, thereby mitigating cardiovascular risk factors [55,56]. A particularly important function of soluble fibers lies in their prebiotic activity; they selectively stimulate the growth and activity of beneficial gut microbiota such as Bifidobacteria and Lactobacilli, fostering a balanced intestinal microbiome that supports improved digestion, enhanced immune function, and overall host well-being. The valorization of these fiber-rich by-products thus represents a promising avenue for sustainable nutrition and health-promoting food development [57].

2.4. Proteins and Bioactive Peptides

Agri-food industry by-products such as oilseed cakes from soybeans, sunflower, and rapeseed, residual grains from brewing processes, and whey derived from dairy production are increasingly recognized as rich, sustainable, and economical sources of high-quality proteins. Once regarded merely as waste, these residues are now being strategically repurposed for their nutritional value, particularly in the context of developing functional health-oriented products [58]. Through enzymatic hydrolysis conducted under carefully controlled conditions, these proteins can be broken down into short amino acid chains known as bioactive peptides. Typically composed of 2 to 20 amino acids, these peptides display a range of targeted biological activities, which are influenced by their amino acid sequence, structural characteristics, and the specific enzymes used during hydrolysis [59].

Research has demonstrated that peptides derived from such sources offer multiple physiological benefits. A well-documented example is their antihypertensive potential through the inhibition of angiotensin-converting enzyme (ACE), a crucial factor in blood pressure regulation. Additionally, many peptides show strong antioxidant activity by scavenging reactive oxygen species, thereby mitigating oxidative stress a contributing factor to various chronic diseases. Others are known to modulate immune responses by influencing cytokine production and stimulating innate immunity, while some exhibit antimicrobial effects by compromising the integrity of microbial membranes or disrupting microbial metabolism [60].

Because of this broad spectrum of bioactivities, bioactive peptides are being actively investigated for inclusion in functional foods, nutraceuticals, and clinical nutrition products designed not only to support general health but also to prevent or manage specific health conditions, such as cardiovascular or inflammatory diseases [59]. Current scientific efforts are centered on optimizing hydrolysis protocols to maximize peptide yield and functionality, as well as enhancing purification and analytical techniques to isolate peptides with the most potent bioactive profiles. In parallel, improving peptide stability and absorption in the gastrointestinal tract is a key focus, aiming to ensure their efficacy when consumed orally. These developments are essential to advancing the practical use of bioactive peptides in modern food science and personalized health strategies [20,27,49].

2.5. Bioactive Lipids

Agri-food residues rich in lipids, such as olive pits, avocado peels, and processing remnants from various nuts, serve as valuable sources of bioactive lipids, including monounsaturated fatty acids (MUFA), polyunsaturated fatty acids (PUFA), tocopherols (a class of vitamin E compounds), and phytosterols. These bioactive lipids are recognized for their broad spectrum of health benefits, including potent anti-inflammatory and antioxidant activities, as well as their ability to reduce serum cholesterol levels by interfering with intestinal cholesterol absorption [49]. The presence of these compounds in lipid-rich by-products underscores their potential for valorization in the development of high-value products [15,18]. Consequently, extracts derived from these residues are increasingly utilized in the formulation of nutraceutical oils aimed at cardiovascular and metabolic health, as key ingredients in dermo cosmetic formulations targeting skin protection and rejuvenation, and as lipid carriers in advanced drug delivery systems that improve the bioavailability and targeted release of pharmaceutical compounds. This multifunctional potential highlights the importance of lipid-rich agri-food by-products in both food and pharmaceutical industries [23,49].

2.6. Pectins and Oligosaccharides

Citrus peels and apple pomace, abundant agri-food by-products, are extensively utilized as principal industrial sources of pectin, a structurally complex heteropolysaccharide composed primarily of galacturonic acid units with varying degrees of methyl esterification and branching [6]. Pectin’s unique physicochemical properties, such as its ability to form gels, act as a thickening agent, and stabilize emulsions, make it an indispensable ingredient in food processing, particularly in jams, jellies, dairy products, and confectioneries [23]. Beyond these technological functions, pectins exert multiple health-promoting effects [49]. These include the modulation of glycemic response by slowing carbohydrate digestion and absorption, reduction of serum lipid levels through binding bile acids and enhancing their excretion, immunomodulatory activities that influence cytokine production and macrophage activation, and positive effects on colonic health by increasing stool bulk and serving as a fermentable substrate for beneficial gut bacteria. Controlled enzymatic or acid hydrolysis of pectins can generate oligosaccharides, short-chain carbohydrate fragments, which have been shown to possess potent prebiotic properties. These pectic oligosaccharides selectively promote the proliferation of advantageous gut microbiota such as Bifidobacterium and Lactobacillus species, leading to improved intestinal barrier function, enhanced production of short-chain fatty acids, and overall gut microbiome balance. This bioconversion significantly elevates the nutritional and functional value of pectins, making them highly attractive for inclusion in functional foods, nutraceuticals, and therapeutic dietary interventions aimed at metabolic and gastrointestinal health [23,27,49].

2.7. Alkaloids

Alkaloids are a diverse group of naturally occurring nitrogen-containing compounds found widely in the plant kingdom, often acting as defense molecules against herbivores and pathogens. Various agri-food residues, including seed hulls, roots, stems, and leafy by-products, represent untapped sources of these bioactive compounds [48]. Particularly, residues from members of the Solanaceae family, such as potatoes (Solanum tuberosum), tomatoes (Solanum lycopersicum), and eggplants (Solanum melongena), are known to contain significant quantities of tropane, pyridine, and steroidal alkaloids. These compounds, while potentially toxic in high concentrations, possess a wide range of pharmacological and ecological functions [61].

From a toxicological standpoint, alkaloids such as solanine and chaconine in potato peels have been documented to cause gastrointestinal and neurological disturbances if consumed in large quantities. This underlines the importance of thorough safety assessments before considering any application involving agri-food residues rich in alkaloids. Risk assessment and dose determination are critical to prevent adverse health effects [62].

Despite their toxicity at elevated doses, alkaloids have drawn increasing scientific and industrial interest due to their potent bioactivities. Many demonstrate antimicrobial properties, effective against a broad spectrum of bacteria, fungi, and viruses. Others, such as berberine and vincristine, show promising anticancer effects through mechanisms like apoptosis induction, cell cycle arrest, and inhibition of angiogenesis. Additionally, certain alkaloids act as natural insecticides, disrupting the nervous systems of pests and reducing crop damage [61]. The valorization of alkaloid-rich agri-food residues, therefore, represents a dual opportunity, mitigating environmental pollution through waste recovery while unlocking new resources for the pharmaceutical, nutraceutical, and biopesticide sectors. To achieve this, interdisciplinary strategies involving green extraction methods, biological activity screening, and toxicological profiling are essential to ensure both efficacy and safety in end-use applications [48,62].

2.8. Saponins

Saponins are glycosidic plant metabolites with amphiphilic properties due to their sapogenin core and sugar chains. Their ability to form foams and interact with membranes makes them valuable for industrial and biomedical uses [63]. Among agri-food residues, saponins are notably abundant in the outer layers and leafy parts of several crops, particularly in legumes such as soybeans, chickpeas, and lentils, as well as in pseudocereals like quinoa. In quinoa seeds, for example, saponins are concentrated in the seed coat, which is typically removed and discarded due to its bitter taste, resulting in large quantities of saponin-rich by-products. These residues, often overlooked, represent a significant and sustainable source of bioactive compounds [64].

Saponins offer a broad range of bioactivities, including antimicrobial, anticancer, anti-inflammatory, and immunomodulatory effects, making them attractive for pharmaceutical and nutraceutical applications [63]. However, at high concentrations, they may cause adverse effects such as gastrointestinal discomfort or nutrient malabsorption, emphasizing the need for controlled use. Their surfactant, emulsifying, and foaming properties also make them valuable in cosmetics, food processing, and detergents. Extracting saponins from agri-food residues like legume hulls or quinoa husks through green technologies supports sustainable development by reducing waste and generating high-value functional compounds [38,63,64].

2.9. Terpenoids

Terpenoids, also known as isoprenoids, constitute the largest and most structurally diverse class of natural products, derived biosynthetically from five-carbon isoprene units. These compounds are abundantly present in a wide range of agri-food by-products, including citrus peels, grape pomace, tomato skins, apple waste, and herbal residues. Common terpenoids found in these matrices include monoterpenes (e.g., limonene, linalool), sesquiterpenes, diterpenes, and triterpenoids such as oleanolic acid and ursolic acid. Carotenoids, such as β-carotene and lycopene, also fall under this category and are especially abundant in carrot pulp, tomato peel, and pumpkin waste [48].

Terpenoids are recognized for their broad spectrum of biological activities. These include potent antioxidant effects through free radical scavenging and enhancement of endogenous antioxidant enzymes, anti-inflammatory action by modulating cytokine production and NF-κB signaling, and anticancer properties via the induction of apoptosis, inhibition of angiogenesis, and suppression of tumor cell proliferation. Moreover, certain terpenoids exhibit antimicrobial and hepatoprotective activities, making them attractive for use in functional foods, dietary supplements, pharmaceuticals, and cosmetics [65]. The recovery of terpenoids from agro-industrial residues using green technologies such as steam distillation, supercritical fluid extraction, or microwave-assisted extraction represents a sustainable approach aligned with circular bioeconomy strategies [48,65].

2.10. Glucosinolates and Isothiocyanates

Glucosinolates are sulfur- and nitrogen-containing secondary metabolites primarily found in cruciferous vegetables and their by-products, such as broccoli stems, outer cabbage leaves, cauliflower cores, and mustard seed cakes. In their original form, glucosinolates are biologically inactive but become active when hydrolyzed by the enzyme myrosinase, which is released when plant tissues are damaged. This enzymatic reaction produces biologically active compounds like isothiocyanates, thiocyanates, and nitriles, with isothiocyanates being especially important for their health benefits. Notable examples include sulforaphane from broccoli's glucoraphanin and allyl isothiocyanate from mustard's sinigrin [66].

Isothiocyanates are recognized for a range of beneficial effects, particularly their chemo preventive action. They promote the induction of phase II detoxifying enzymes (e.g., glutathione S-transferase), suppress phase I enzymes involved in carcinogen activation (such as cytochrome P450), and influence epigenetic regulation. Additionally, they reduce inflammation by inhibiting pro-inflammatory cytokines and enzymes like COX-2 and exhibit antimicrobial activity against various pathogens. Reports also highlight their neuroprotective and cardioprotective effects, underscoring their potential in functional foods, nutraceuticals, and pharmaceuticals. Utilizing enzyme-assisted or pressurized liquid extraction techniques to recover glucosinolates and their active derivatives from agricultural wastes supports sustainable resource use and adds value to these by-products [67]. Table 1 illustrates the main classes of bioactive compounds and their corresponding sources in agri-food by-products.

Table 1. Major classes of bioactive compounds and their agri-food byproduct sources.

Group	Subgroup/type	Agri-Food By-product Sources	References
Polyphenols	Flavonoids	Apple peels, grape skins, onion skins, olive leaves	[41,68–71]
	Phenolic acids	Pomegranate peel, grape pomace, rice bran	[69,72,73]
	Tannins	Olive mill wastewater, grape seeds	[41,74]
	Stilbenes	Grape skins, peanut skins	[69,73]
Carotenoids	β-carotene, Lycopene, Lutein, Zeaxanthin	Carrot pulp, tomato skins, citrus peels, pumpkin waste	[75–77]
Dietary Fibers	Soluble fibers (pectin, inulin, gums)	Fruit pomace (apple, citrus), cereal bran, chicory root, oilseed cakes	[78,79]
	Insoluble fibers (cellulose, lignin)	Cereal husks, fruit peels, vegetable residues	[78,80]
Proteins and Peptides	Bioactive peptides	Soybean meal, sunflower cake, rapeseed meal, whey, brewers' spent grain	[81–83]
Bioactive Lipids	MUFA, PUFA, Tocopherols, Phytosterols	Olive pits, avocado peels, nut skins and shells	[84,85]
Pectins and Oligosaccharides	Pectins, pectic oligosaccharides	Citrus peels, apple pomace	[68,86]
Alkaloids	Tropane, Steroidal, Pyridine alkaloids	Potato peels, tomato stems, eggplant waste	[48,76]
Saponins	Triterpenoid, Steroidal Saponins	Soybean hulls, sugar beet pulp, quinoa husks, chickpea pods, alfalfa stems	[81,87]
Terpenoids	Mono-, Sesquiterpenoids	Citrus peels, mint leaves, tomato waste	[76,88]
Glucosinolates	—	Cauliflower stems, broccoli leaves and stalks	[89,90]
Isothiocyanates	Sulforaphane, Allyl isothiocyanate	Broccoli stems, mustard seed cake, cabbage cores, radish skins	[89–91]

3. High-Value Agrifood By-Products Valorization Methods

Agrifood residues are recognized as valuable feedstocks due to their rich content of bioactive compounds, macronutrients, and functional biomolecules with diverse properties; however, they are often discarded or underutilized [92–94]. So, valorizing these by-products into high-value products has become important in transitioning toward a sustainable bioeconomy [95,96].

This section provides an in-depth overview of the main technologies employed to recover these by-products, such as green extraction techniques, biological valorization, enzymatic hydrolysis, encapsulation, and even thermochemical methods (Figure 3).

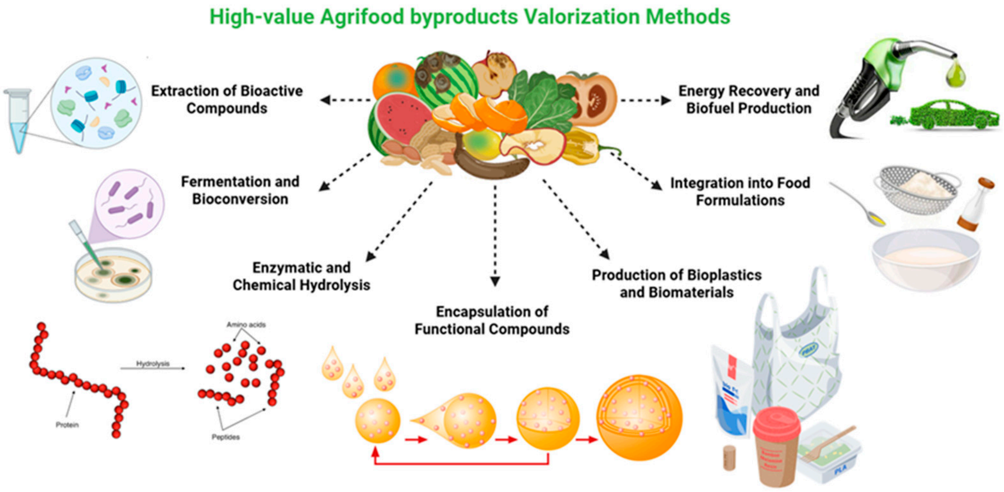

Figure 3. Agrifood by-products valorization methods.

3.1. *Extraction of Bioactive Compounds*

Fruit peels and vegetable scraps are a common food waste, so it's essential to recycle them because they are rich in biologically active compounds such as antioxidants, phenolic acids, flavonoids, dietary fiber, etc. [97]. They also have numerous health benefits, so they must be extracted and utilized [38]. There are several methods, including: First, Ultrasound-Assisted Extraction (UAE), Živković et al. [98] extracted phenolic compounds from pomegranate peel by breaking the walls and tissues of the hard plants using sound waves. They found this method to be simple, highly efficient, and low in solvent consumption [98,99].

Another method is Microwave-Assisted Extraction (MAE), Bagade and Patil [100], produced and extracted some bioactive compounds from citrus peels using microwave energy to raise the solvent temperature, facilitating the dissolution and diffusion of the active compound. This method proved to be highly effective compared to traditional methods. Recently, an innovative and environmentally friendly method called Supercritical CO_2 Extraction (SFE) has emerged. Studies conducted by Uwineza and Waśkiewicz [101] demonstrated that this method extracts highly purified oily substances that can be used in several fields, such as pharmaceuticals, cosmetics, and other applications. Under critical conditions, CO_2 enables extraction without solvent-related damage or contamination.

3.2. *Fermentation and Bioconversion*

To convert agricultural, food, or even industrial by-products into other high-value products, fermentation and bioconversion have been found to be effective methods. These methods utilize microorganisms or enzymes based on their metabolic activity [102]. There are two common methods for fermentation: the first is Solid-State Fermentation (SSF), which is a method for synthesizing enzymes in which microorganisms grow in a solid, dry medium. The second is Submerged

Fermentation (SmF), which is the reverse method, where microorganisms grow in a liquid and is specifically designed to produce organic acids and ethanol [103,104].

There are several studies, such as those conducted by Lima et al. [104], who succeeded in producing enzymes using SSF from wheat bran and sugarcane bagasse using the fungi Aspergillus niger and Trichoderma reesei. Similarly, Bejenaru et al. [103], were able to ferment pomegranate and mango peels using the same method, converting them into antioxidant-rich products. Shrestha et al. [105], successfully produced lactic acid from fruit and vegetable waste using Lactobacillus spp., but using the SmF method.

In addition to the two previous methods, another approach, known as "Bioconversion", involves the enzymatic conversion of molecules, such as sugars, phenols, or starches, into more biologically active compounds, including aglycones, short-chain fatty acids, and phenolic metabolites [106]. Several studies have investigated this method. For example, T. Wang et al. [107] modified citrus peel flavonoids using Bacillus subtilis while Nurmilah et al. [108] converted soybean isoflavones into aglycones using Aspergillus oryzae.

3.3. Enzymatic and Chemical Hydrolysis

Enzymatic and chemical hydrolysis play an important role in the valorization of by-products, as they facilitate the breakdown of proteins and polysaccharides from industrial and agricultural waste to produce bioactive substances. Proteins can be hydrolyzed into peptides and free amino acids through the action of proteases, acids, or alkalis Enzymatic hydrolysis is often considered the preferred approach because it acts selectively on specific compounds, operates under mild conditions, and causes less structural damage compared to chemical methods [109].

Hunsakul et al. [110] in their study focus on using alcalase to make peptides from rice bran protein. Pepsin and trypsin useful in the pharmaceutical and food industry are also produced when using fish waste, according to the study by Ortizo et al. [111].

On the other hand, another method known as polysaccharide hydrolysis involves breaking down starch, hemicellulose and cellulose into oligosaccharides or monosaccharides through the action of enzymes such as cellulase, hemicellulase and amylase [112]. As a result, fibers end up being turned into fermentable sugars or active oligosaccharides like xylo-oligosaccharides (XOS) and fructo-oligosaccharides (FOS) [113]. Among the research on this approach, F. Yan et al. [114] found that XOS compounds from wheat and maize straw increased the amount of Bifidobacterium when they were hydrolyzed by xylanase. They have also proven that a multi-enzyme complex can produce oligosaccharides and fermentable sugars from cassava waste to support bioethanol production [115].

3.4. Encapsulation of Functional Compounds

Compounds present in by-products are often likely to deteriorate quickly and become unstable. For these reasons, herbs are more effectively used when they are encapsulated, allowing them to be stored for longer with higher bioavailability [116]. Heat-sensitive substances can be carefully used with spray drying methods. Heating from hot air helps to turn these liquid extracts into powder in this method. Nguyen et al. [117] reported a method to extend the shelf life of acai juice by using encapsulated polyphenols.

New approaches like nano and liposome use allow active medications to be encased in particles to increase both safety and use within the body. According to Ghadiri Amrei et al. [118], nano-liposomes help protect curcumin derived from turmeric and enhance its ability to penetrate cell membrane, making it particularly useful for applications in the food and pharmaceutical industries.

Biopolymers such as chitosan, whey protein, gelatin and alginate are also widely used as encapsulation materials and carriers. Phupaboon et al. [119] reported that the carriers can encapsulate active ingredients within very thin membranes. Similarly, Paulo et al. [120] utilized whey protein to encapsulate phenolic extracts from olive waste, resulting in a product suitable for fortifying dairy products and dietary supplements.

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3.5. Production of Bioplastics and Biomaterials

In response to the demand for eco-friendly products, bioplastics and biomaterials are now being produced from agro-industrial residues such as husks, stalks, peels and shells. These eco-friendly materials reduce waste and contribute to the transition away from fossil fuel–derived products [121].

Among all biodegradable thermoplastics, PLA stands out as a major material because it can be produced from recycled fruit peels, corn stover and sugarcane bagasse. Taib et al. [122] reported that Lactobacillus species ferment agro-waste sugars and convert them into lactic acid, which is subsequently polymerized into PLA with higher yield and lower cost. Another class of biodegradable plastics, known as polyhydroxyalkanoates (PHAs), is produced by microorganisms such as Cupriavidus necator and Bacillus species cultivated on carbohydrate-rich wastes, including molasses, fruit scraps, and hydrolyzed lignocellulose. Thamarai et al. [123] found that potato peels and olive mill wastewater, as substrates for PHA production yielded a high polymer content, enabling the resulting PHA material to exhibit thermoplastic properties.

Combinations of natural fibers such as banana, jute, rice husk, and wheat straw with biodegradable or bio-based resins improve the mechanical properties, decrease the products' weight, and reduce environmental impact. Laftah et al. [124] reported that incorporating rice husks into PLA improved its strength and heat resistance. The use of banana fibers has also revealed potential in packaging applications. For instance, Freitas et al. [125] developed food packaging films from wheat straw and thermoplastic starch, which performed successfully in all tests.

3.6. Integration into Food Formulations

Fruit pomace, vegetable peels, and bran can be converted into ingredients for food that are rich in fiber, antioxidants, unsaturated fats, and bioactive substances. This approach not only reduces food waste but also addresses consumer demand for clean and health-promoting products. After juice production, the remaining solid waste contains plenty of fiber and nutrients, which can be processed into powder and incorporated into bakery foods [126].

Adding apple pomace into wheat flour bread has been shown to increase fiber levels, more antioxidants, and improve taste for consumers [127]. Similarly, grape pomace has been successfully used to enrich cookies with polyphenols and antioxidants without affecting their taste or texture [128]. Food dressings and spreads can also be improved with cold-pressed oils from grape, pumpkin, and tomato seeds, which are rich in unsaturated fatty acids, vitamin E, phytosterols, and antioxidants.

Vegetable peels from carrots, potatoes, beetroots and onions are rich in phenolics, carotenoids and flavonoids and can be dried and used in soups and similar dishes to increase their nutritional and antioxidant value. Chabi et al. [129] reported that incorporating carrot peel powder increased the antioxidant content and beta-carotene levels in tomato soup, without altering its taste. Likewise, quercetin extracted from onion peel has shown potential in seasoning powders and broths due to its anti-inflammatory and antioxidant properties [130].

3.7. Integration into Food Formulations

Energy and biochar can be produced from food byproducts through processes such as anaerobic digestion, pyrolysis, combustion, and transesterification. During anaerobic digestion, organic matter decomposes in the absence of oxygen, generating both biogas and digestate.

Co-digesting fruit and vegetable waste with cattle manure, as reported by Yan et al. [131], not only led to increased production of methane but also stabilized the digestion process. Saravanan et al. [132] described how anaerobic digestion can benefit food industries by producing bioenergy near the source and reducing pollution. Meanwhile, valorization of lignocellulosic materials into biochar and energy is achieved through pyrolysis and combustion processes.

Rahimi et al. [133] demonstrated that slowly heating rice husk in a reactor resulted in biochar containing more carbon and produced syngas for heating. The resulting biochar also improved soil quality and contributed to reducing greenhouse gas emissions. More recently, Ohile et al. [134]

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successfully converted mango kernel oil into biodiesel with high efficiency and quality. Similarly, Jamil [135] reported that agricultural residues are suitable feedstocks for biodiesel production, particularly for use in rural and off-the-grid areas.

4. Analysis of Relationship Between Agrifood By-Products Valorization and Key SDGs

Previous studies found in the relevant literature revealed a close relationship between food waste and by-product valorization and the achievement of Sustainable Development Goals (SDGs). For example, SDG 1 (No Poverty) can be advanced by creating employment opportunities and income streams through biomass conversion and bio-based industries. SDG 2 (Zero Hunger) contributes to food security by reducing losses and promoting more efficient food systems. SDG 3 (Good Health and Well-Being) is supported through the development of functional foods and nutraceuticals from agro-waste, improving nutrition and public health. SDG 5 (Gender Equality) is promoted by empowering women through participation in agri-food value chains and waste-to-resource initiatives, fostering inclusive opportunities. SDG 6 (Clean Water and Sanitation) benefits from reduced agro-industrial effluents, which limit water pollution. SDG 7 (Affordable and Clean Energy) is addressed through the production of renewable energy carriers such as biogas, bioethanol, and biomass pellets. SDG 8 (Decent Work and Economic Growth) is promoted by generating new economic activities and value chains in waste-to-resource sectors. SDG 9 (Industry, Innovation, and Infrastructure) is strengthened through the adoption of innovative biomass conversion and waste management technologies. SDG 12 (Responsible Consumption and Production) focuses on resource recovery and the transformation of waste into value-added products. SDG 13 (Climate Action) is supported through reduced greenhouse gas emissions, particularly methane and carbon dioxide, thereby contributing to climate change mitigation. SDG 14 (Life Below Water) benefits from lower nutrient-rich discharges into aquatic environments, helping prevent eutrophication and protecting marine biodiversity. Finally, SDG 15 (Life on Land) is reinforced through sustainable land management and biodiversity conservation, reducing pressures such as deforestation, land expansion, and habitat loss. The following section will discuss these points in detail (Figure 4).

4.1. SDG 1: No Poverty

SDG 1, through Targets 1.1–1.5, focuses on poverty alleviation, with Target 1.4 emphasizing the need to ensure equal access to basic services, economic resources, and social protection in order to strengthen the resilience of vulnerable populations [136]. Upcycling or valorizing food is considered a technological approach to retain both the nutritional and economic value of food waste and byproducts [137]. This strategy can enhance food security and social well-being by improving access to nutritious diets and generating income, thereby helping to reduce poverty. However, its impact is shaped by market dynamics, as reducing waste may lower food prices, making food more accessible to consumers but potentially reducing farmers' earnings [34].

Therefore, it is essential to shift from current agricultural practices to more holistic approaches such as agroecology, climate-smart agriculture, and sustainable agriculture [138]. The adoption of these practices by farmers enhances agricultural productivity. Arouna et al. [139] reported that the adoption of improved rice varieties between 2000 and 2014 in 16 sub-Saharan African countries significantly enhanced productivity, income, and food security. On average, farmers gained US$ 3.9 per capita annually, with incomes rising from US$ 25 to US$ 58. In 2014, this progress lifted around 1 million households (8 million people) out of poverty and 0.9 million households (7.2 million people) out of food insecurity. Livestock, crop cultivation, and fisheries are central to the socio-economic progress of both rural and urban populations, providing food, livelihoods, and trade opportunities. In Kenya, the mango value chain, including fresh fruit and processed products, represents a substantial contributor to agricultural Gross Domestic Product and foreign exchange revenues [140]. Beyond these direct economic benefits, the valorization of agri-food byproducts and waste holds considerable potential for stimulating local economies, with estimated values ranging from –$100 to $138 per ton [9]. Globally, the annual economic cost of food loss and waste is estimated at approximately US$680 billion in developed countries and US$310 billion in developing countries [141]. By transforming what is often discarded into marketable goods, such initiatives can diversify income sources, foster small-scale enterprises, and create employment opportunities, thereby improving the living standards of vulnerable and low-income communities [142].

Furthermore, reducing food loss and waste benefits both suppliers and consumers. By cutting losses, farmers, processors, and retailers can boost productivity, increase sales, and reduce disposal costs. Consumers also save money by wasting less and may gain from lower food prices, making these measures an effective contribution to poverty reduction [143].

Figure 4. Impact of agrifood by-products and waste valorization on sustainable development goals (SDGs).

4.2. SDG 2: Zero Hunger

SDG 2, through Targets 2.1–2.5, addresses critical aspects of food security and sustainable food systems, with Target 2.4 placing particular emphasis on sustainable production methods and resilient agricultural practices. At the same time, the global population is projected to reach nearly 10 billion by 2050, which will create a 56% gap between current food availability and future needs. Currently, around 800 million people still suffer from hunger, even though one-third of all food produced, equivalent to about one billion tons, is lost or wasted each year [144]. Agriculture, while indispensable, is also a major driver of deforestation, accounts for 70% of freshwater withdrawals, occupies nearly half of vegetated land, and generates about one-quarter of global greenhouse gas emissions. The rising demand for resource-intensive foods further intensifies pressure on ecosystems and the climate [145].

In this context, reducing food losses by 25% and converting organic waste and agri-food byproducts into valuable products such as food ingredients, fertilizers, and animal feed could substantially improve food availability, enhance nutrition, and strengthen food security, particularly in resource-constrained regions [34,146], while also mitigating environmental impacts [147]. Estimates suggest that reducing agro-industrial waste by 30–50% could increase the global food supply by at least 15% [148]. As previously noted, food waste and byproducts represent an important reservoir of essential nutrients, including proteins, complex carbohydrates, lipids, and phytochemicals. They are particularly rich in polysaccharides, dietary fibers, oils, vitamins, phenolics, carotenoids, and other compounds that could help eradicate hunger [45]. Spiker et al. [149] estimated that the energy contained in wasted food could supply about 273 kcal per person per day, equivalent to nearly 15% of the global median recommended daily intake. Similarly, large proportions of key micronutrients such as zinc, copper, manganese, and selenium, ranging from 25% to 50% of daily requirements, are also lost through food waste [150].

From previous studies, food fortification plays a vital role in addressing malnutrition, with several initiatives focusing on the use of agrifoos waste and byproducts [151]. Consequently, in developing countries, the valorization of these residues can contribute to the production of food additives that help combat malnutrition and hunger. In West Africa, Oludipe et al. [152] reported that the byproducts of Parkia biglobosa seeds have potential applications in various industries, including food, cosmetics, pharmaceuticals, and agriculture. Similarly, in Cameroon, peels of Musa paradisiaca and Musa acuminata have been identified as a primary raw material for producing traditional food salts, known as Nikkih, which are commonly used in the preparation of yellow achu soup owing to their emulsifying properties [153]. In Algeria, fortifying pasta with whey powder as a partial replacement for wheat flour could help address the deficit of animal proteins in the diet [154]. Moreover, biotechnological processes can reduce antinutritional factors, making these byproducts suitable for balanced food formulations and strengthening food security [142]. Passion fruit peels and seeds were processed into flour and used to fortify drinkable yogurt. The incorporation increased fiber, minerals (K, Mg, Mn), and viscosity, while affecting color and shelf life (21 days) highlighting passion fruit byproducts as a promising ingredient for nutritious and marketable yogurts [155].

In summary, the valorization of food waste and agri-food byproducts represents a promising strategy to improve nutrition, reduce hunger, and strengthen food security. Ultimately, their integration can help bridge the gap between rising food demands and limited natural resources.

4.3. SDG 3: Good health and Well-Being

SDG 3, through Targets 3.1–3.9, seeks to ensure healthy lives and well-being by reducing preventable mortality, addressing non-communicable diseases, and strengthening healthcare systems. Agrifood by-products and food waste valorization directly contributes to this goal by enabling the recovery of bioactive compounds, functional proteins, and essential nutrients from agri-food byproducts, which can be used in nutraceuticals, functional foods, and dietary supplements [45]. Such innovations not only improve population health and nutrition but also reduce reliance on synthetic additives and pharmaceuticals, thereby lowering associated health risks. Moreover, valorizing food waste into safer, nutrient-rich products supports preventive healthcare strategies, promotes healthier diets, and mitigates the public health burden of malnutrition and diet-related diseases, aligning with the broader objectives of SDG 3 [142,156].

Previous studies show that annual per capita food waste could provide a nutritionally adequate diet for 18 days [150], and reducing food losses by half will improve nutritional intake and positively impact chronic health conditions like heart disease and type II diabetes [157]. C. Chen et al. [150] further reported that food waste contains 25–50% of daily requirements for several micronutrients, including vitamins B6, C, and K, as well as selenium, copper, zinc, iron, and manganese. They introduced the concept of “wasted daily diets (WDD),” defined by the lowest wasted nutrient days (WND) across 25 nutrients. If fiber yields the lowest WND at 40 days, this means one person’s annual food waste could sustain an adequate diet for 40 days or feed 40 people for a single day. Valorization pathways also contribute to improved nutrition; for example, Okara, a soybean byproduct, can be transformed into dairy-based beverages through solid-state fermentation, producing probiotics alongside dietary fiber, free isoflavones, and essential amino acids [158]. Similarly, a multi-country study in Kenya, Cameroon, and India showed that food loss and waste drive significant micronutrient losses, suggesting that reducing post-harvest losses in developing countries could enhance intake of critical nutrients such as iron and vitamins A and C [159]. Overall, valorizing food waste and byproducts improves nutrition, prevents diet-related diseases, and directly advances SDG 3.

4.4. SDG 5: Gender Equality

SDG 5, through Targets 5.1–5.6, emphasizes achieving gender equality and empowering all women and girls. Specifically, it focuses on ending discrimination and violence, eliminating harmful practices, ensuring equal participation in leadership, and promoting universal access to reproductive health and rights. In the context of agrifood waste and by-product valorization, SDG 5 underscores the importance of strengthening women’s participation in sustainable value chains, supporting their role in entrepreneurship and innovation, and ensuring equitable access to opportunities arising from circular bioeconomy initiatives [160].

From previous studies, Cantaragiu [161] have reported that gender influences attitudes and behaviors toward food waste. While women tend to show greater concern for its social and financial impacts, they may also engage in practices that generate more waste. Similarly, Yoon et al. [162] highlighted gender difference in food consumption and sustainable behavior. Compared to men, women tend to favor environmentally friendly restaurants, show greater willingness to buy sustainable products, express stronger concern for environmental issues, and pay higher prices for sustainably produced food. In Bangladesh, however, educated women, particularly those involved in balcony gardening, effectively implement the 5R strategies, with composting as a central practice. These efforts enhance sustainability, reduce costs, and create income opportunities, thereby empowering women to combat food waste [163]. In Rwanda, Surchat et al. [160] studied the experiences of men and women working informally in biowaste recycling. Through photovoice and interviews, they found that workers valued social connections, productivity, and savings, but faced health risks, tough conditions, and low pay. Gender differences appeared in marital status and access to jobs opportunities. Despite these challenges, recycling improved workers' well-being and showed that circular economy initiatives can create meaningful green jobs in both sexes. Moreover, Noel [164] reported from a study of 390 solid-waste workers in Port-au-Prince, Haiti, that the sector includes all age groups but shows clear gender differences, with men and women performing distinct roles. Health outcomes also varied: women more often reported respiratory, digestive, and skin problems, while men experienced sprains, eye irritation, and colds. Despite gender differences in consumption behavior and waste management practices, the sector of waste and agri-food by-product valorization offers significant potential to promote gender equality. Through the employment opportunities it creates, this sector contributes to women's empowerment and, consequently, supports the achievement of SDG 5 objectives.

4.5. SDG 6: Clean Water and Sanitation

SDG 6, through Targets 6.1–6.6, underscores the importance of ensuring universal access to clean water and adequate sanitation, while safeguarding water quality and promoting sustainable management of water resources. In particular, Target 6.4 emphasizes improving water-use efficiency across all sectors and ensuring the sustainable withdrawal and supply of freshwater to address water scarcity. In the context of agrifood waste and by-product valorization, SDG 6 underscores the role of circular practices in reducing water pollution, advancing water-efficient processing technologies, and mitigating the environmental impacts of agro-industrial residues, thereby contributing to cleaner water systems and sustainable ecosystem management [165].

From literature, water scarcity is a growing global concern, with increasing demand from agriculture, industry, and households exerting unprecedented pressure on freshwater resources [166]. Agriculture consumes 64–69% of the annual 1212–1452 km^3 available, while the olive oil industry further amplifies pressures through high water use and effluent generation. Climate change is expected to exacerbate these vulnerabilities, as increased temperatures and altered precipitation regimes intensify droughts, wildfires, and domestic water shortages, further constraining agricultural productivity and expansion in the region [167]. Considering these challenges, the valorization of agri-food waste and by-products becomes a key strategy to advance SDG 6 by mitigating the environmental burden of effluent discharges. Agro-industrial processing, particularly in the dairy, meat, fruit, and olive oil sectors, produces wastewater streams enriched in organic matter, fats, phenolic compounds, and nutrients such as nitrogen and phosphorus [168,169]. If released untreated, these effluents accelerate eutrophication, reduce oxygen levels, and foster microbial contamination of aquatic systems, thereby compromising both water quality and public health [170]. Through innovative valorization strategies, such as anaerobic digestion, composting, fermentation, and the extraction of bioactive compounds, these effluents can be transformed into value-added products while significantly reducing pollutant loads [171]. Olive mill wastewater has recently attracted attention as a low-cost feedstock for valorization, particularly for the recovery of phenolic compounds with strong antioxidant properties. Several extraction methods have been explored, including enzymatic treatments, solvent-based techniques, chromatographic separation, and membrane processes. These natural antioxidants hold significant potential for diverse applications, notably in the food industry as functional ingredients and natural preservatives that enhance nutritional value and extend shelf life [169]. Moreover, the management of dairy effluents traditionally relies on a combination of physicochemical and biological treatment strategies. Physicochemical options include coagulation–flocculation, membrane-based separations, and related technologies [172], whereas biological treatments encompass both aerobic and anaerobic systems such as activated sludge, stabilization lagoons, sequencing batch reactors, and up flow anaerobic sludge blanket reactors [173]. These systems not only facilitate the remediation of pollutants but also enable the simultaneous recovery of value-added products, such as bioelectricity, hydrogen, and other bioenergy carriers, thereby coupling wastewater treatment with resource valorization [172]. Such approaches not only improve the circularity of the agri-food sector but also minimize water consumption in processing plants by promoting wastewater recycling and safe re-use in agricultural irrigation.

Moreover, integrating by-product valorization into agro-industrial supply chains aligns with emerging policies on water resource management and wastewater reuse, fostering a transition towards cleaner production systems. Beyond reducing pollution, these practices support the development of decentralized wastewater treatment technologies, which are particularly relevant in water-scarce regions. By simultaneously addressing issues of water quality and availability, the valorization of agri-food by-products constitutes a powerful pathway to advance the targets of SDG 6, while also generating significant economic and social co-benefits. This approach embodies a broader transition towards a sustainable agricultural sector, one that shifts away from the prevailing linear “take–make–dispose” paradigm of resource consumption and embraces instead a circular model based on “reduce, reuse, recycle, and regenerate” [174].

4.6. SDG 7: Affordable and Clean Energy

SDG 7, through Targets 7.1–7.3, addresses key dimensions of ensuring universal access to affordable, reliable, sustainable, and modern energy. Target 7.2 emphasizes a substantial increase in the share of renewable energy in the global energy mix, while Target 7.3 focuses on doubling the global rate of improvement in energy efficiency. Together, these targets highlight the importance of transitioning towards cleaner energy systems that support economic growth, mitigate climate change, and promote environmental sustainability.

According to previous studies, approximately US$1 trillion in economic value and 26×10^9 GJ of energy are lost globally each year through food waste [175]. In this context, the valorization of food waste and agri-food byproducts emerges as a powerful strategy to support the global transition towards clean energy [9,176]. Organic residues can be converted into renewable energy carriers such as biogas, bioethanol, biohydrogen, and biomass pellets, providing sustainable alternatives to fossil fuels while reducing the environmental burden of waste management. Among the different valorization pathways, fuel production is generally the most economically attractive, yielding USD 200–400 per ton of biomass, whereas electricity generation and animal feed production provide comparatively lower values of USD 60–150 and USD 70–200 per ton, respectively [177]. For instance, a decentralized system converting food waste into energy demonstrated that 30 kg of waste produced 0.55 L CH_4/g VS (Volatile Solids), while a scaled-up operation processing 500 kg/day generated 74.8 kWh of electricity. Further optimization increased energy output significantly, with electricity production rising by 135% and thermal energy by 87%, highlighting the potential of such systems to simultaneously mitigate waste and deliver clean energy [176]. In Nairobi City County, organic waste accounts for 58–63% of municipal solid waste, with food waste comprising 64% of recoverable materials. With a biomethane potential of 508.45 ml CH_4/g VS, the city’s food waste could generate 10.5 million m^3 of methane, equivalent to about 1.38 MW of electricity [178]. Similarly, a bioconversion strategy using black soldier fly larvae combined with microbial treatment was employed to convert rice straw and restaurant solid waste into biodiesel. Within 10 days, 2,000 larvae reared on a 1,000 g substrate consisting of 30% rice straw and 70% restaurant solid waste produced approximately 43.8 g of biodiesel. The results indicated that grease obtained from larvae grown on this mixed feedstock represents a viable raw material for biodiesel production, with fuel properties largely compliant with international standards [179].

Finally, agrifood byproducts and waste not only contribute to climate change mitigation by lowering greenhouse gas emissions but also enhances energy security by diversifying local energy supplies. The deployment of bioenergy solutions derived from agri-food residues can stimulate rural development by creating green jobs, generating additional income streams for farmers, and expanding energy access in off-grid or underserved communities.

4.7. SDG 8: Decent Work and Economic Growth

SDG 8 promotes inclusive and sustainable economic growth, productive employment, and decent work for all. It emphasizes supporting entrepreneurship and job creation (Target 8.3) while improving resource efficiency and decoupling growth from environmental degradation (Target 8.4), thereby fostering innovation and sustainable economic practices.

In the context of agrifood waste and byproduct valorization, these targets create opportunities for job creation, entrepreneurship, and the development of green industries [9]. SDG 8 aligns with efforts to transform food waste into value-added products such as biofuels, bioplastics, and nutraceuticals, thereby enhancing resource efficiency, reducing environmental pressures, stimulating local economies, and supporting sustainable economic growth [180]. Food waste valorization also generates added value that can expand employment opportunities for local populations, providing additional social benefits [142]. Furthermore, it fosters innovation and market expansion by promoting industries dedicated to waste reduction, recovery, and recycling. These advancements can further stimulate economic growth and enhance market competitiveness [23].

Conversely, the adoption of circular economy strategies and improvements in resource efficiency are anticipated to generate over 500,000 jobs while cutting annual CO_2 emissions by more than 400 million tons [181]. In Rwanda, a survey of 63 workers in composting and biowaste processing showed that conditions are generally decent by national standards, though limited by weak social protection and safety measures. Worker satisfaction was moderate, with notable differences between composting and processing employees [182]. However, new technologies and the use of robotics may reduce unskilled jobs in agrifood valorization (SDG 8), potentially contributing to migration, unemployment, and poverty if not accompanied by adequate social support. At the same time, automation could help address labor shortages in areas where urbanization and an ageing workforce restrict production [183].

4.8. SDG 9: Industry, Innovation and Infrastructure

SDG 9, through Targets 9.1–9.5, promotes resilient infrastructure, sustainable industrialization, and innovation. Specifically, it emphasizes expanding industrial contribution to employment and GDP (Target 9.2) and strengthening research and technological capacity (Target 9.5). In the context of agrifood waste and byproduct valorization, SDG 9 highlights the role of innovative technologies and industrial processes in transforming waste into value-added products, thereby enhancing resource efficiency, reducing environmental impacts, and fostering sustainable economic growth [45].

Previous studies highlight that advances in digitalization, innovation, and process optimization in the food manufacturing sector, such as Industry 4.0 technologies and modern infrastructure development, can indirectly support SDG 9 by enhancing industrial efficiency, fostering innovation, and strengthening infrastructure [184]. Currently, industries are focusing on innovations aimed at achieving zero waste, where agrifood by-products and waste are repurposed as raw materials for the creation of new foods [142]. For example, aquaculture is increasingly adopting innovative feed solutions. For instance, NovaCQ is a bioactive feed ingredient produced through the bioconversion of low-value agricultural by-products [185]. Additionally, some agrifood by-products are utilized to fortify new food products; for instance, whey powder has been used as a partial replacement for wheat flour in pasta production, thereby helping to address dietary protein deficiencies [154]. Moreover, technologies such as near-infrared spectroscopy and hyperspectral imaging, when combined with computer vision and smartphone tools, facilitate the monitoring of food quality, safety, and authenticity. These approaches help reduce waste and support the objectives of SDG 9 [186].

Hanumante and Maitre [187] further emphasize that resilient infrastructure is crucial for advancing agro-biomass valorization, however, limited facilities and incentives restrict its progress. Strengthening infrastructure and innovation is therefore vital for expanding value-added biomass use.

4.9. SDG 12: Responsible Consumption and Production

SDG 12, through Targets 12.1–12.8, addresses the need to ensure sustainable consumption and production patterns across sectors. Target 12.3 emphasizes halving global food waste at the retail and consumer levels and reducing losses along production and supply chains, while Target 12.5 focuses on substantially reducing waste generation through prevention, reduction, recycling, and reuse. In the context of a circular economy, processes such as anaerobic digestion and composting act as important pathways for generating organic fertilizers. Food waste–based compost, in particular, can be incorporated into cropping systems to rehabilitate degraded soils, thereby enhancing soil fertility and supporting higher agricultural yields [188]. Digestate is recognized as an effective soil amendment for improving fertility. Fertilizers derived from food waste valorization not only enhance soil productivity and food security but also mitigate the environmental impacts associated with food waste accumulation and disposal [189]. Promoting responsible consumption, automatic and electric composters are increasingly adopted in households, restaurants, and schools to recycle food waste efficiently while generating valuable compost [190]. Likewise, chitin and chitosan from crustacean waste provide sustainable alternatives in packaging, preservation, nutrition, and eco-friendly pesticides [191].

In the same way, sustainable food consumption requires coordinated stakeholder action and the integration of sustainability into supply chain management, supported by policy frameworks that promote awareness and enforce food loss and waste reduction [192]. Alternative protein sources such as edible insects, underutilized legume crops, unexploited terrestrial and aquatic weeds, and yeast proteins offer environmentally beneficial, scalable, and nutritionally valuable options [193]. Singapore illustrates the urgency of responsible consumption: despite importing over 90% of its food, it generates about 759 tons of food waste annually. To counter this, the government launched the Zero Waste Plan and the 30-by-30 strategy, aiming to reduce waste, improve resource efficiency, and meet 30% of nutritional needs through local production by 2030 [158]. Evidence also links responsible consumption with better adherence to dietary guidelines [194], while poor compliance can undermine health, as seen in Ethiopia where nearly 80% of pregnant women missed iron and folic acid supplementation [195]. Overall, these findings highlight the critical role of policies, byproduct recovery, and awareness initiatives in fostering responsible consumption and building sustainable food systems [196].

4.10. SDG 12: Responsible Consumption and Production

SDG 13, through Targets 13.1–13.3, emphasizes strengthening resilience and adaptive capacity to climate-related hazards, integrating climate change measures into national policies, and enhancing education and awareness on mitigation and adaptation. Specifically, Targets 13.2 and 13.3 highlight the importance of mainstreaming climate action into governance frameworks and building institutional capacity.

The global food system contributes 25–34% of greenhouse gas (GHG) emissions, with uneaten food alone accounting for 8–10% [22,197]. Food wastage generates an estimated 3.3 billion tons of CO_2 annually, with environmental impacts ranging from −347 to 2969 kg CO_2-eq per ton, and consumes 1.4 billion hectares of land, equivalent to 28% of global agricultural area. In developing and low-income countries, most losses occur during production, while in middle- and high-income regions, waste is concentrated at the retail and consumer levels [9]. Consequently, valorizing food waste and byproducts offers a sustainable solution by reducing landfill methane emissions, conserving natural resources, and producing renewable energy [9].

Previous studies have reported the per capita climate change impact of food waste as 0.53, 0.45, 0.48, 0.58 and 0.14 tons CO_2-eq in the U.S., Canada, UAE, KSA, and Japan, respectively [198]. Effective valorization strategies, however, can significantly mitigate these emissions. For instance, in the United States, converting food waste into higher-value industrial products could reduce emissions by approximately 1.9×10^8 tons of CO_2-eq annually [199]. Similarly, using a life cycle assessment (LCA), Berge et al. [200] evaluated the environmental impacts of hydrothermal carbonization (HTC) of food waste and subsequent hydrochar combustion for energy generation. Their findings indicated a net negative global warming potential (GWP) for all substituted energy sources except biomass, with reductions ranging from –32.6 to –190.0 kg CO_2-eq per ton of food waste. M. H. Kim et al. (2013) showed that anaerobic digestion had a net GWP of 33 kg CO_2-eq (211.0 kg CO_2-eq/ton), co-digestion with sludge a higher impact (259.0 kg CO_2-eq/ton), while drying followed by incineration achieved –315 kg CO_2-eq through renewable energy recovery and material substitution. In summary, food waste valorization reduces GHG emissions, supports SDG 13 through resilience and resource efficiency, and contributes to global climate goals when integrated into national policies.

4.11. SDG 14: Life Below Water

SDG 14, through Targets 14.1–14.7, emphasizes the conservation and sustainable use of oceans, seas, and marine resources. Specifically, it highlights the need to reduce marine pollution, protect aquatic ecosystems, and promote sustainable fisheries. In the context of agrifood waste and by-product valorization, SDG 14 underscores the role of sustainable aquaculture and innovative feed solutions in reducing environmental impacts, minimizing nutrient runoff, and supporting healthy marine ecosystems [201]. Prabakusuma et al. [202] highlight that valorizing agrifood wastes and by-products, such as leaf flours, bran, molasses, oilseed meals, fruit residues, and surplus starches, offers a sustainable strategy for aquaculture feeds by lowering costs, reducing environmental impacts, and supporting the circular bioeconomy. Furthermore, the disposal and recycling of agrifood by-products and waste represent a sustainable strategy within the circular bioeconomy, enabling the production of high value-added materials [203]. Similarly, an estimated 30–35% of captured seafood is lost or discarded globally, representing a valuable resource that could be converted into highly nutritious ingredients to partially replace fishmeal in aquafeed formulations [204].

Since feed represents 60–75% of the total cost of fish production, incorporating agrifood by-products and waste as low-cost feed sources in aquaculture can reduce financial losses for the agrifood sector while simultaneously lowering costs along the fish supply chain, thereby improving fishers' incomes [205]. This, in turn, can indirectly benefit marine ecosystems and support SDG 14.

4.12. SDG 15: Life on Land

SDG 15, through Targets 15.1–15.9, aims to protect, restore, and promote the sustainable use of terrestrial ecosystems, halt biodiversity loss, combat desertification, and ensure the sustainable management of forests. Agrifood by-products and food waste valorization contributes to this goal by reducing land degradation, minimizing agricultural residues that threaten soil and ecosystem health, and fostering circular bioeconomy practices that support biodiversity conservation and sustainable land use [206,207].

From previous studies, the recovery and reuse of agricultural residues, processing by-products, and food waste can substantially reduce the need to convert natural habitats into agricultural land, thereby limiting encroachment into forests, wetlands, and other ecologically sensitive areas [208]. For instance, the use of crop residues, olive pomace, or fruit peels as soil amendments, organic fertilizers, or animal feed not only recycles essential nutrients but also maintains soil fertility and prevents land degradation [209].

Valorization strategies play a crucial role in promoting resilient and sustainable farming systems. By encouraging diversification beyond monocultures, which are significant drivers of biodiversity loss, these approaches help maintain a wider variety of plant and animal species within agricultural landscapes. Closing nutrient loops through the reuse of organic residues and by-products reduces the reliance on synthetic fertilizers and other chemical inputs, thereby protecting soil microbial communities and preserving the health of surrounding ecosystems [208]. In addition, incorporating by-products into agroecosystem management not only enhances carbon sequestration and increases soil organic matter, but also improves water retention, which is essential for maintaining soil fertility under variable climatic conditions. These combined effects strengthen ecosystem resilience, mitigate land degradation, and contribute to the long-term sustainability of agricultural production [210]. Ultimately, such strategies create synergies between environmental conservation, resource efficiency, and productive farming, supporting a more circular and sustainable agricultural model [211].

At the landscape scale, circular approaches that convert agricultural and industrial residues into value-added products can create strong economic incentives for the conservation of semi-natural habitats and the maintenance of buffer zones. By generating value from existing resources rather than encouraging the expansion of cultivated land, these strategies reduce pressure on natural ecosystems and promote multifunctional land use [212]. This approach allows agriculture to coexist with conservation by protecting native species, restoring degraded areas, and promoting sustainable land management. When combined with organic farming, which emphasizes soil health, nutrient cycling, and ecological interactions while reducing synthetic inputs [213], the benefits of circular practices are amplified. Together, they enhance ecosystem services such as biodiversity, soil fertility, and water regulation, contributing to environmental sustainability and rural socio-economic development in line with SDG 15.

5. Challenges and Limitations

While agri-food waste and byproducts valorization holds significant potential for advancing sustainability, health, and economic development, several challenges limit its widespread adoption. Technological barriers remain prominent, particularly due to the heterogeneity, seasonality, and variability of agri-food waste streams, which complicate the design of standardized processing techniques. Many valorization methods, such as enzymatic hydrolysis, encapsulation, or bioconversion, are still at the laboratory or pilot scale, with limited translation into cost-effective industrial applications. Additionally, the lack of resilient infrastructure and advanced technologies in many regions restricts large-scale biomass processing and value-added product development.

Economic and policy limitations further hinder progress. High initial investment costs, limited financial incentives, and insufficient policy frameworks reduce private sector engagement. In many low- and middle-income countries, weak regulatory structures and underdeveloped waste management systems exacerbate inefficiencies and reduce opportunities for innovation.

From a social perspective, occupational safety, inadequate social protections, and informal labor remain critical issues for workers in waste collection and processing sectors. Moreover, socioeconomic inequalities often restrict equitable distribution of benefits, leaving rural and small-scale producers marginalized.

Finally, environmental and research challenges persist. Inconsistent data availability undermines accurate life cycle assessments, while context-specific conditions, such as energy infrastructure, local markets, and regulatory frameworks, limit the generalizability of findings. Addressing these constraints is essential to fully harness the potential of agri-food byproducts and waste valorization and to realize its contribution to multiple Sustainable Development Goals.

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6. Conclusions and Future Prospective

The valorization of agri-food byproducts offers a powerful pathway to simultaneously reduce environmental burdens, enhance resource efficiency, and generate economic and social benefits. By converting waste streams into high-value compounds, biofuels, biomaterials, and functional ingredients, this strategy contributes to multiple Sustainable Development Goals, including food security, clean energy, responsible production, and climate action. Moreover, it fosters innovation, supports green industries, and creates opportunities for employment and local economic growth. However, despite its promise, the field still faces significant challenges. Limited industrial scalability, inadequate infrastructure, insufficient regulatory frameworks, and high processing costs remain major barriers to widespread adoption. Furthermore, unequal access to technology and markets restricts the inclusion of smallholder farmers and low-income communities in the value chain. Looking ahead, advances in digitalization, Industry 4.0, and biotechnology hold great potential to optimize processes, improve efficiency, and expand applications for agri-food byproducts.

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