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A comprehensive review of food waste valorization for the sustainable management of global food waste

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Food waste (FW) is a global problem and a hidden opportunity for the value-added product conversion. Thus, food waste valorization is a growing science toward the waste-to-wealth conversion. FW can be generated either on a domestic or industrial scale, even if a zero-waste policy is practiced, owing to the unavoidable portion of food waste generated during the processing, cooking, and transportation of food materials. Previous studies have reported that FW is a potential sink for valuable bioactive molecules and bioenergy. In addition, earlier reports noted that the application of contemporary and advanced valorization processes for food waste management was limited to developed countries, and a significant portion of FW remained untouched owing to the lack of research in the rest of the global arena. As a result, this comprehensive review scrutinized several vital and advanced options for the sustainable valorization of global food waste, focusing on its prospects and challenges. In particular, this study deciphers the potential of unexplored valorization approaches and integrated biorefinery strategies for the holistic management of global food waste. Owing to the unavoidable waste generation during food processing, handling, and transportation, the sustainable valorization of FW is a phenomenal option for meeting the sustainable development goals (SDGs) of the United Nations (UN). Finally, this review paves the way for adopting sustainable technologies to convert waste into wealth through integrated valorization and biorefinery approaches toward the efficient recycling of global food waste.

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Sustainability spotlight

In the modern society, food waste derived from households (kitchens) and industries is considered a critical environmental concern because of its underutilization and the lack of sustainable recycling. Moreover, food waste and industrial streams are sources of hidden bioactive molecules and value-added products. Despite numerous possibilities for food waste management, the waste-to-wealth conversion through sustainable approaches is limited. Consequently, the potential of food waste remains unexplored because of the lack of sufficient research and policymaking. Thus, this comprehensive review summarizes the existing approaches towards food waste valorization, including cutting-edge sustainable technologies for the proper utilization and recycling of unutilized but potential waste streams in light of SDG 2 (zero hunger), SDG 7 (affordable and clean energy), and SDG 12 (responsible consumption and reproduction).

1. Introduction

In the global context, one of the most common types of biowaste generated today is food waste (FW). The manufacturing, handling, storage, processing, distribution, and consumption of food largely contributes to the quantity of global FW generation.^{1,2} One of the ways towards food-waste management is to segregate the FW into edible and non-edible waste during its disposal.² Over the last decade, food processing has become one of the fastest-growing industries in the world and a considerable amount of waste is produced during the processing of food. According to statistics, the production, distribution, and retail of food and beverages account for approximately 20% of the

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total 14 MMT of the waste generated annually.³ The fruit and vegetable (F & V) industry generates more waste compared to other food processing sectors, accounting for 25–30% of the total waste, which might be anything from peels and rinds to seeds, cores, rags, stones, pods, vines, skins, and pomaces.⁴ The processing of fruits and vegetables generates a massive amount of trash, and the proper disposal of this waste increases overall production costs. Therefore, in most situations, fruit and vegetable wastes are discarded into the environment to reduce the production costs.⁵ As fruit and vegetable waste is biodegradable, it decomposes rapidly, emitting unpleasant odors. If not managed promptly, this can lead to significant environmental and health issues. Fruits and vegetable waste that is improperly disposed of can produce germs and attract disease-carrying insects, such as flies and mosquitoes. It can also contaminate the surface and groundwater, leading to phytotoxicity⁶ and significant health-related issues.^{6,7}

A daily diet that includes at least five servings of fruits and vegetables has been shown to significantly lower the risk of several chronic illnesses and the onset of age-related issues.⁸ Fruits and vegetables have special health advantages because of their abundance of bioactive substances; these include phenolic compounds, terpenes, terpenoids, alkaloids, flavonoids, carotenes, and other bioactives.^{9,10} Bioactive compounds, including primary metabolites, such as proteins, carbohydrates (cellulose, hemicellulose, lignin, and pectin), and lipids, are often found in fruits and vegetables. These bioactive compounds are typically present at very low concentrations in these foods. Plants produce these metabolites to thrive and enhance their ability to withstand environmental stress, diseases, and sunlight.¹⁰ These biologically active molecules have antioxidant, antibacterial, and anti-inflammatory properties that help combat chronic diseases, such as oxidative stress. The efficacy of these compounds depends on their bioactivity, chemical structure, and dosage used.¹¹

Governments and the food industry have made it one of the top priorities to eliminate or significantly reduce food waste. Waste valorization in a circular economy involves the production of valuable products, such as fuels, materials, and chemicals. In addition to producing value-added goods, such as organic fertilizers, animal feed, biofuels, and electricity from food waste, it contributes to economic, social, and environmental improvements.^{12,13} Over the last decade, numerous studies have focused on the transformation of value-added products from FW, including edible ingredients, functional foods, nutraceuticals, medicines, and cosmetics.^{14–17}

However, additional factors must be considered to ensure the suitability of industrial processes for various matrices. Ensuring adaptability to a variety of matrices, integrating all biorefinery plant activities, and maintaining environmental and economic sustainability are the essential aspects to consider. Therefore, choosing a particular extraction technique for one or more classes of bioactive compounds from waste depends on the compromise between different factors. The recovery and reuse of waste and by-products were performed according to a circular economy model that includes the concepts of biorefinery and industrial symbiosis. The goals of the relevant technologies and

techniques are increased sustainability, no or reduced organic solvent usage, and minimal environmental effects. Furthermore, new procedures have recently been developed to chemically characterize vegetable and fruit waste and by-products, including sample preparation. This method has replaced conventional methods of solvent extraction using organic solvents, which can pose environmental and health concerns.^{18–21}

In particular, circular economy practices are implemented for sustainable recycling and utilization of neglected agri-food wastes,^{22,23} while developing countries are still suffering from food waste due to the lack of economic funds, public awareness, and political will, among others.^{24,25} Developing countries such as China, Serbia, and India have started to implement such principles,^{26–28} although FW valorization will benefit through the circular economy regardless of countries' status across the world.^{29–31}

Novel, easier, sustainable, safe, greener, and more cost-effective approaches for extracting value-added products that can be utilized as clean labels in food systems have been the subject of ongoing research. This review explores innovative eco-friendly methods for extracting bioactive compounds from fruit and vegetable wastes, particularly for food applications. This article compares these techniques to traditional processes, highlighting the advantages of biorefinery processes, including reducing waste generation, creating new revenue streams, combining multiple technologies, sharing resources, and possibly attaining energy self-sufficiency by producing biogas or using inert fiber materials as fuel.³² Research on the integrated exploitation of plant-derived waste in the production of diverse goods has evolved over the last decade.³³ Therefore, this review aims to provide an updated summary of the most recent integrated processing techniques applied to different agriculture-derived waste or by-products toward sustainable recycling. Finally, sustainable recycling and the biorefinery processing of food wastes are critically discussed for sustainable waste management.

2. Review motivation and literature arrangement

In recent decades, food waste recycling and valorization have been considered a growing sustainable research theme worldwide. Thus, the literature search and arrangement were squeezed, scrutinized, and confined within the specified keywords during data archive collection for this comprehensive review to meet the specific objectives of this review. According to previous investigations, advanced food waste recycling and valorization approaches were practiced by specific countries but were limited in the rest of the world. Consequently, food waste containing hidden resources remains untapped, particularly on an industrial scale. According to the United Nations (UN) Sustainable Development Goals (SDGs), food waste management is highly recommended for the attainment of SDG 2 (zero hunger), SDG 7 (affordable and clean energy), and SDG 12 (responsible consumption and production). Therefore, the prime goal of this comprehensive review was to explore food waste as a global concern and the existing valorization



approaches to strengthen the sustainable development goals of the United Nations. We carefully collected and thoroughly assessed previously published papers, including original research and review articles. We aimed to identify the main challenges in managing global food waste sustainably and to understand the primary issues faced during implementations. For this purpose, we utilized specific keywords such as "food waste recycling," "food waste generation," "valorization of food waste," "food waste circular economy," "food waste stream," "sources of food waste," "food waste conversion," "challenges of food waste valorization," and "solution for food waste management." We conducted searches using renowned scholarly search engines, such as Web of Science, Scopus, Google Scholar, and reputable publishers' websites, to gather relevant data for this review.

The selected data archives were skimmed and narrowed down to meet the specific goals of this comprehensive review. The basic steps were the selection of raw data, exclusion/inclusion, revising the data archive, and finalizing literature for this review paper but we did not follow any structured review protocol. Although this review does not adhere to a specific methodology, its central theme revolves around sustainable global food waste management. It emphasizes the contemporary technologies for food waste recycling and their role in achieving the Sustainable Development Goals (SDGs) set forth by the United Nations. Initially, the collected papers (approximately 400, including original research and review papers) were critically analyzed, and the most relevant papers were finally chosen for establishing the review theme. The core ideas and highlights of this review, following critical evaluation, are summarized in Fig. 1.

3. Food waste and environmental concern: a global macro problem

Food waste, food loss, and food surplus are the key terminologies of global food waste generation.³⁴ In general, food waste

can be defined as a specific part of edible food that becomes inedible as a result of anthropogenic and pest damage, intentional waste, pre- and post-harvest losses, and immature consumption during the food supply chain.^{3,35,36} However, food waste is considered an emerging concern throughout the world. Substantial nutritional, environmental, and economic losses are evident from global food waste due to detrimental consequences and management complexities.³⁷⁻³⁹ The nutritional and economic losses caused by food waste have been studied globally. Approximately 35% of the total loss of food was documented through different stages of the food supply chain, from production (pre-harvesting) to consumption (post-harvesting) pathways.¹ Additionally, a combined and pioneer appraisal was reported to focus on the compound nutritional and environmental consequences of food waste in a global context.³⁸ Previous studies have noticed a positive correlation between greenhouse gas (GHS) footprint and water footprint with the reduction of global food waste.^{38,40} Intensive agriculture with hybrid and exhaustive crop species may require a large amount of major macronutrients, such as nitrogen and phosphorus. A countable amount of global nitrogen was lost through food waste at various food supply chain processes on a European scale.⁴¹

Several global and regional studies have explained the global challenges of food in terms of nutritional, environmental, and economic aspects.^{1,38,39,42} Food waste is also called Food Loss and Waste (FLW). The generation of FLW has been facilitated through various household and kitchen wastes in several countries around the world without proper recycling.^{1,43} The recent global pandemic (COVID-19) and the resulting lockdown in many affected countries may seriously threaten the current food waste management policies. Thus, food waste has emerged as a global threat due to poor management in such an adverse global pandemic.⁴⁴ Consequently, global food waste and food loss have been reported as priority research themes for highly industrial regions of the world.⁴⁵ Therefore, global environment and food entities such as the United Nations Environment Programme (UNEP), Food and Agriculture Organization (FAO),

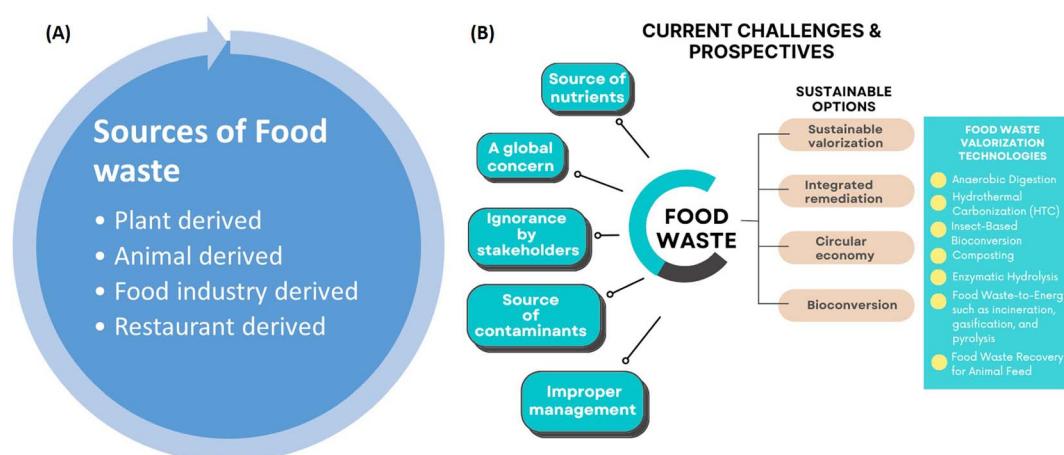


Fig. 1 A schematic showing the global food waste originating from various sources (A) and current challenges and perspectives (B). The figure data were extracted from the critical summary of previous studies and is displayed to pinpoint the key findings of the review theme.



and International Food Policy Research Institute (IFPRI) have revised several rules and act with respect to food waste minimization to sustain food security and food safety, and reduce global hunger.^{34,35,37} Thus, waste-to-wealth technology and sustainable recycle, reduce, reuse, and recovery (4R) waste management concepts have been attempted to manage food waste in a sustainable environment policy.⁴⁵⁻⁴⁷

3.1. Agri-food waste and environmental pollutants

FW derived from agricultural goods has been reported as a potential bio-toolkit for soil improvement due to the inclusion of numerous nutrients.^{48,49} Pesticides, trace metals, volatile organic compounds (VOCs), and other emerging pollutants may limit the use of FW as a soil amendment in the long run.^{49,50} Chemical substances that have been present in the environment for a long time but have recently gained prominence owing to human activities are known as emerging contaminants (ECs).^{51,52} Antibiotics, pesticides, pharmaceuticals, nanoparticles, medicinal equipment, hormones, industrial materials, personal care items, veterinary medicines, contaminated and spoiled food, fertilizers, and hazardous metabolites have all been identified in agricultural areas as potential ECs.^{53,54}

Soil contamination by ECs is a worldwide problem, and its effects unreasonably impact the global pollution index because of their increased industrial and developmental activity.⁵⁵⁻⁵⁸ Numerous studies have shown that pesticides are used indiscriminately over acceptable levels in many populous nations, including India and Bangladesh.^{53,59} In underdeveloped nations, the World Health Organization (WHO) reports approximately 3 million cases of pesticide poisoning and 22 000 deaths per year.⁶⁰ Additionally, the widespread use of pesticides for the past five to six decades has resulted in increased health risks for all living things, including humans, due to the environmental degradation caused by the explosive growth of the pesticide industry.^{53,61}

The illustration (Fig. 2) shows that surface runoff, agricultural irrigation, and precipitation can transport emerging contaminants through the food chain. These pollutants are now detected in several fresh and processed foodstuffs, such as fruits, vegetables, livestock, and fish, as well as in soil and water

sources.^{53,62,63} In addition, plastic pollutants, including microplastics and nanoplastics, can accumulate and translocate through food waste into the food web chain, posing a great threat to aquatic and terrestrial food systems.^{64,65} The rising release of pollutants into water and soil poses a serious concern, as it endangers local plants and wildlife, harms soil fertility, and causes toxicity to soil organisms. Additionally, it contributes to antibiotic resistance in soil bacteria, hinders plant growth, and diminishes the survival and reproductive capabilities of soil invertebrates.⁶⁶ The unpredictability of environmental pollutants such as heavy metals in FW might be viewed as a major impediment to protracted recycling and valorization of FW for agricultural purposes and value-added products.^{63,67} Although some microbiological and enzymatic degradation of pesticides and heavy metals has been studied, including MSW,^{52,68} further extensive and meticulous studies for sustainable recycling of FW are needed.

4. Food waste stream: a hidden treasure of bioactive molecules

Most organic waste and food industries leave huge byproducts as food waste streams. Food waste streams derived from the food industry are considered sources of diverse nutrients and bioactive compounds.^{46,47,69} Various food industries, such as fruit juice, cheese making, and brewery, are sources of essential minerals and nutrients. Carbohydrates, cellulose, hemicellulose, proteins, lignin, pectin, lipids, and antioxidants are the major detected nutrients and valuable compounds in the food waste streams of major food industries, including potato, cereal, fish, and fruit processing.⁷⁰ Vegetable waste streams are a neglected portion of the food industry worldwide. However, the vegetable waste stream has been reported as a rich source of extracted pectin (a heteropolysaccharide derived from cell walls and lamellae of vegetables). Early observations documented the potential of rejected vegetable waste streams (carrot, green bean, and leek) from the food industry to extract commercial pectin.⁶⁹ A recent study explored the conversion of wet waste streams in the USA into valuable biofuels, bioenergy, and bio-products using waste-to-energy (WtE) approaches.⁷¹ Based on the study findings, four different wet wastes, namely, food waste, animal manure, sewage sludge, and oil, fat, and greases, were used in the WtE approach. All wet wastes, excluding oil, fat, and greases, were converted through conventional waste management strategies, including anaerobic digestion and incineration for bioconversion into valuable energy and biofuels.

Food loss is considered a critical global threat due to the negligence of nutrient and energy-rich food waste streams derived from major food industries. The Food and Agriculture Organization (FAO) of the United Nations has observed that the food loss in industries occurs because of the improper disposal of food waste streams by these respective industries.⁷⁰ This leads to a considerable loss of potential nutrients and energy-rich food due to the improper management of food waste streams. Therefore, food waste valorization is receiving the

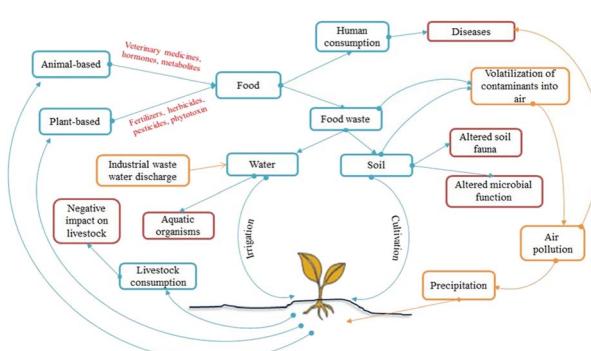


Fig. 2 A simplified diagram showing the interaction of legacy chemicals and the chemicals of emerging concern, while food waste acts as the building block.



researchers' attention to convert discarded food waste into high-value products and energy. The unscrupulous disposal of food waste due to regional ignorance of waste management rules causes environmental damage and economic challenges for the global circular economy. An encouraging review explained the conversion potential of several food waste streams into valuable biopolymers such as cellulose, chitin, collagen, lignin, hemicellulose, xanthan gum, organic acids, cooking oil, etc.⁷² The valorization from food waste streams is a sustainable approach concerning the circular economy, green environment, and recovery of valuable neglected food nutrients through conversion into precious bioproducts.⁷⁰ The resource recovery (RR) strategy is linked to the water–energy–food cycle and is used to predict both sustainable economic turnover and environmentally friendly performance.⁷³ The resource recovery technique is beneficial in the economic and socio-technical realms concerning the sustainable management of food waste streams. Thus, the sustainable and profitable conversion of food waste streams into valuable products was suggested for a win–win circular economy by properly managing industrial waste streams.^{47,72–74} The food waste stream management through various sustainable approaches is tremendously important for sociotechnical acceptance, in addition to environmental aspects.^{74,75} A list of commonly used food wastes associated with bioactive compounds is given in Table 1.

5. Contemporary valorization approach for food waste conversion

Food waste valorization is an emerging strategy for converting various types of food waste into value-added products. To boost the circular economy approach, different innovative and sustainable anaerobic digestions have been optimized for efficient food waste management.⁴⁴ Application of immobilized enzymes has also been reported to meet sustainable economic returns through bioconversion of food waste into valuable resources.⁴³ Previous research has reviewed conventional (orthodox) and innovative (emerging) valorization approaches for vegetable and fruit wastes.¹¹⁷ However, conventional practices of food waste management may include animal feeding of surplus food materials, orthodox landfilling, composting for organic manure, and incineration as thermal treatments. The aforementioned individual techniques face challenges because of their limited efficiency, high energy consumption, high moisture content, low calorific value, variable composition, and potential contamination. These traditional methods can indirectly increase economic profits, but they may lead to the loss of valuable biomaterials extracted from food waste streams. Critical resource depletion, including nutrients and bioactive compounds, and adverse environmental impacts were predicted due to conventional and unplanned food waste management.¹¹⁸ Therefore, integrated and emerging household and food waste management was encouraged to meet the global legal frameworks for food security. Furthermore, traditional waste management poses multiple challenges to achieving sustainable development goals. These challenges include the

generation of greenhouse gases, higher costs without value-added products, the release of high temperatures, and various air pollutants.^{118–120} Although several conventional approaches such as composting and vermicomposting, combustion, or incineration with proper landfilling may have a positive correlation with sustainable economic and environmental aspects, the commercialization of waste valorization through conventional management of food waste is still limited.^{117,120}

Anaerobic digestion, composting, source degradation, and *in situ* conversion of several wastes, including food waste, food processing waste, and agricultural residues, have been reported as effective schemes for the conversion of food waste into biofertilizers.¹²¹ However, the resultant biofertilizers can replace a portion of the applied synthetic fertilizers in a waste valorization approach. Similarly, a contemporary study noticed four sustainable livestock waste valorization approaches. The approaches included anaerobic co-digestion and mono-digestion using biological drivers, gasification, and pyrolysis (thermal technology) to replace conventional landfilling and incineration strategies.¹²² The integrated food waste management through valorization was anticipated by both institutional bodies and consumers' participation. A survey evaluated Italian consumers' willingness and overall perception toward food waste valorization. The study depicted a comprehensive scenario between the consumers and concerned authorities to participate actively in sustainable food waste management through various valorization techniques, either by conventional or emerging approaches.¹²³ Furthermore, a combination of sustainable, environmentally friendly, renewable, and inexpensive approaches to waste management toward a circular bioeconomy has been suggested.¹²⁴ According to the findings of several conceptual, behavioral, empirical, and cohesive studies, global optimization and synchronization efforts have been made to establish a circular bioeconomy through food waste valorization. To date, both traditional and contemporary methods of food waste valorization have been merged to create an integrated waste management plan within a European context that also applies to developed nations worldwide. However, the emerging enzymatic conversion of food waste into value-added compounds has become a priority in the sustainable food waste valorization race in the industrially driven regions of the world.^{74,75,117}

6. Conversion of value-added products from horticulture waste (HW)

Horticultural waste (HW) is an unavoidable waste generated during the harvesting of fruits and vegetables from the field and during the processing of fruits and vegetables in the food industry.^{125,126} Several variables and procedures in 'farm to fork' food web chains (*i.e.*, harvesting techniques, processing factors, peeling factors, and feedstock heterogeneity) can influence the cohort of HW derived from fruits and vegetables.^{127,128} These HWs act as reservoirs for numerous bioactive molecules and extractable value-added products.¹²⁹ Good numbers of recent research and review papers have documented the perspective of



Table 1 Bioactive compounds from food waste streams and by-products

Categories	Primary constituents	Type of waste	Methods of extraction	Ref.
Carbohydrates	Pectin, chitin and chitosan, cellulose, xanthan gum, polyhydroxylalkanoate, polyhydroxybutyrate	Citrus fruits, apple pomace, sweet potato pulp and peel, carrot, crustacean shells	Freeze drying, acid-assisted solvent extraction, centrifugation, ethanol extraction, ultrasonic degradation, supercritical CO_2 extraction	6 and 76–84
Phenolic compound	Chlorogenic acid, caffeic acid, ferulic acid, <i>p</i> -coumaric acid, sinapic acid, <i>p</i> -coumaroyl-quinic acid, hydroxybenzoic acid, gallic acid, ferulic acid, hydroxy-cinnamic acid derivatives, chlorogenic acids, geraniin, corilagin, gallic acids, ellagic acid, ellagitannins, chlorogenic acid, vanillic acid	Olive mill wastewater, white grape pomace, apple pomace, peel and pulp of orange, lemon, plum pomace, mango kernel seed, banana peel, sweet cucumber, rambutan, dragon fruit, pineapple, guava, potato peel, beetroot pomace, broccoli	Concentration, acid-assisted solvent extraction, ethanol precipitation, concentration, dilution, micro-filtration, ultra-filtration, supercritical fluid extraction, microwave-assisted extraction, ultrasound-assisted extraction, pressurized liquid extraction, enzyme-assisted extraction	85–95
Flavonoids	Isorhamnetin, kaempferol, quercetin, rhamnetin glycoconjugates, procyanolidin b ₂ , (–)-epicatechin, eriocitrin, hesperidin, narirutin, quercetin, isoquercitrin, fisetin, rutin, quercetin, kaempferol, myricitin, laricitrin, catechin, epicatechin	Apple pomace, citrus peel, mango kernel, banana peel, beetroot, broccoli	Solvent extraction, supercritical fluid extraction, microwave-assisted extraction, ultrasound-assisted extraction, pressurized liquid extraction, enzyme-assisted extraction	85–90, 93 and 94
Phytochemicals	Anthocyanins, carotenoids, betalains, lycopene	Apple pomace, plum pomace, mango peel, carrot, banana peel, berries, beetroot, tomato pomace and peel	Enzymatic hydrolysis, solvent extraction, subcritical water extraction, microwave-assisted extraction, ultrasound-assisted extraction, pressurized liquid extraction, enzyme-assisted extraction	88, 94 and 96–99
Organic acids	Acetic acid, fumaric acid, citric acid, lactic acid, succinic acid, propionic acid, gluconic acid	Waste cheese whey, apple industry waste biomass, apple pomace ultrafiltration sludge, banana peel, citrus peel waste, fruit and vegetable waste, fruit and vegetable waste, apple pomace, sugarcane molasses	Fermentation	100–108
Lipid	Grape seed oil, triglycerides, free fatty acids (linoleic, palmitic, and oleic acids)	Brewers' spent grain, grape seeds	Soxhlet extraction, pressurized carbon dioxide extraction with compressed carbon dioxide as solvent and ethanol as co-solvent	109 and 110
Bioactive peptides	Angiotensin-converting enzyme (ACE) inhibitory peptides, antioxidant peptides, anti-inflammatory peptides, antidiabetic peptides, antihypertensive peptides, lactokinins, lactoferricin, immunoglobulin-derived peptides	Fish processing waste (head, bones, and skin), whey protein by-products, soybean residues, white grape pomace	Water extraction, ultrasonic-assisted extraction, enzymatic-assisted extraction, alkaline solubilization, and acid precipitation, precipitation (isoelectric precipitation), high voltage electrical discharge, skimming, micro-filtration, ultra-filtration, filtration, freeze drying,	81 and 110–114



Table 1 (Contd.)

Categories	Primary constituents	Type of waste	Methods of extraction	Ref.
Lignans	Syringaresinol and secoisolariciresinol	Flaxseed waste and sesame seed hulls	enzymatic hydrolysis, fermentation	109 and 110
Essential oils	Orange oil, lemon oil, grapefruit oil, oregano oil, thyme oil, rosemary oil, cinnamon oil, grape seed oil, vanilla oil, pumpkin seed oil, and almond oil	Citrus peels, herb and spice residues, grape pomace, vanilla pods, seed and nuts waste, plum seed	Enzymatic-assisted extraction Cold pressing, steam distillation, solvent extraction, supercritical fluid extraction, microwave-assisted hydro-distillation	115 and 116

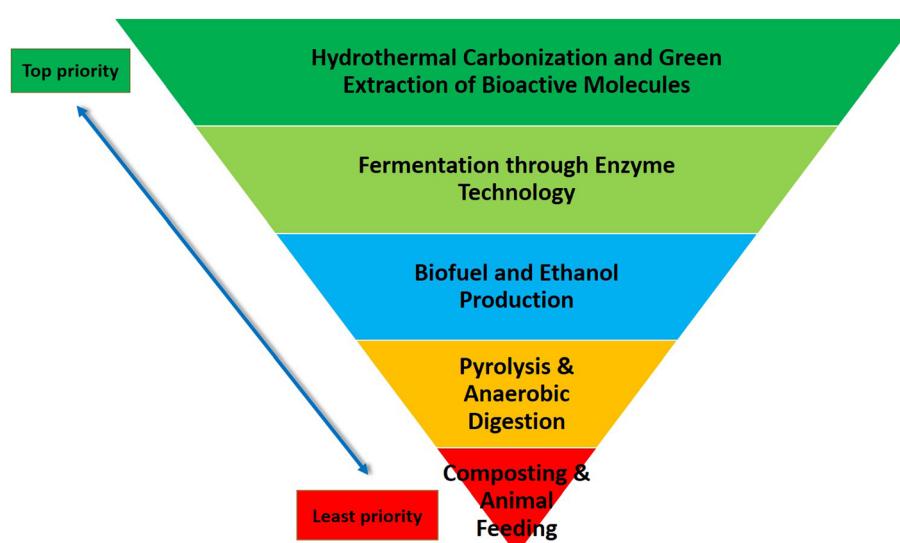


Fig. 3 A hypothetical hierarchy pyramid of food waste management and the valorization approach deciphering the least priority to top priority approaches. This figure depicts the vital points concerning policy implications toward advanced food waste recycling.

a 'waste to value' strategy toward sustainable management of horticultural and agricultural wastes.^{33,126,130–132} Although waste from fruits and vegetables is regarded as a possible source for various new value-added goods, the untapped potential of sustainable techniques for this 'waste to value' approach has yet to be fully explored.^{125,133} Therefore, the bioconversion and extraction of high-value products from fruit and vegetable wastes should be meticulously explored Fig. 3.

Generally, waste derived from fruits and vegetables is the key harbor of many significant biomolecules, including carbohydrates, proteins, lipids, and volatiles.^{134,135} If fruit and vegetable waste valorization is not correctly managed, these valuable but unusable or unrecognized bioactive compounds may be lost. However, several conventional and advanced approaches for the sustainable bioconversion of HW into value-added products have been reported.^{126,136} HW is heterogeneous and largely composed of peels and seeds of fruits and vegetables.¹³⁷ Thus, a major bioactive molecule of HW is either an essential oil (flavoring products) or a preservative (secondary metabolites). In addition, the pulp of HW may contain other bioactive

materials such as carotenoids, sugars, and vegetative tissues, including lignocellulose fibers.^{125–137} Despite the potential of HW, its sustainable bioconversion and utilization in large-scale biorefineries are limited.¹³⁸ Among the bioactive compounds derived from fruit and vegetable wastes, organic acids have been the most reported.¹²⁷ For instance, citric acid has been extracted from banana and citrus peel wastes, apple pomace wastes, etc.¹³⁹ Succinic acid, and lactic acid have been extracted from wheat bread and apple wastes,¹⁴⁰ respectively.

HW, particularly fruit and vegetable waste (FVW), is a rich source of bioactive materials and dietary fibers compared to edible portions.¹⁴¹ Consequently, a large portion of inedible and unavoidable FVW remains untapped for the extraction of high-value compounds compared to the edible portions of horticultural crops.^{129,142} Several emerging high-value bioactive compounds such as polyphenols, biofuels, and biodiesel have been extracted from agricultural residues and horticultural waste.^{68,137,143} Amongst the high-value compounds, essential oils, carotenoids, phenolic compounds, saponins, sterols, phytic acids, and polyphenols have been extensively studied and



extracted from the HW derived from fruits and vegetables.^{129,144} In addition, several antioxidants and antimicrobial activities of the extracted bioactive molecules from FVW suppressed *Listeria*-oriented foodborne diseases in humans.^{129,145} Likewise, the by-products of fruits and vegetables have been considered potential feedstocks for extracting several dietary fibers.¹⁴⁶

Several classical and modern extraction approaches have been found to be effective in extracting these potential high-value compounds from HW.¹⁴⁷ Traditional extraction methods such as vigorous grinding, maceration, drenching, Soxhlet, heating, and supercritical fluid extractions are highly discouraged during sustainable bioconversion of fruit and vegetable wastes, owing to high energy inputs and cost-effectiveness concerns.^{148–150} Eventually, several modern extraction methods have replaced older techniques and have emerged as green and sustainable approaches for converting agricultural waste into valuable resources. These methods include microwave-assisted, ultrasound-assisted, pressurized solvents, enzymatic extraction, negative pressure extraction, and high-pressure homogenization.^{99,147} In contrast, uncertain byproduct generation during conventional extraction approaches is doubtful.¹⁴⁷ So, alternative green extraction solvents are beneficial and sustainable with regard to uncertain toxicity.^{151,152} However, anaerobic digestion (AD) is considered a robust approach for the effective bioconversion of FVW into value-added products.¹⁵² Thus, the adoption of advanced and sustainable extraction strategies for the efficient bioconversion of HW will open new avenues for food waste valorization (Table 2).

7. Integrated biorefinery: an innovative approach

Integrated valorization methods involve a combination of various waste treatment and conversion processes to maximize the value extracted from waste streams, including food waste. These integrated approaches aim to enhance resource efficiency, reduce waste, and support sustainability. Integrated valorization methods can include a combination of biological, chemical, and thermal processes as well as the recovery and utilization of valuable byproducts. Over the last few years, advanced strategies have explored HW, specifically FVW, for the production of high-value bioactive compounds, bioenergy, and biofuels.^{175,176} The 'waste-to-energy' concept was adopted for biomass conversion from FVW into bioenergy and biofuels.^{125,126,131} Several potential 'waste-to-energy' approaches, such as landfilling, composting, anaerobic digestion, enzymatic conversion, *etc.*, have been documented for efficient biorefinery of HW.¹²⁶ Among the adopted approaches, anaerobic digestion (AD) is the most efficient for large-scale industrial bioconversion of fruit and vegetable wastes.¹⁵² However, various value-added products, including bioenergy, biofuel, biohydrogen, biodiesel, bioethanol, and volatile fatty acids, have been extracted from horticultural wastes.^{125,177,178} Similarly, a previous observation¹⁷⁹ noted the potential of agri-food wastes for the sustainable management of wastewater through bioconversion of FVW biomass.

The biorefinery of HW (*i.e.*, pineapple waste into value-added products, and synthesis of nanoparticles from horticultural wastes) has been documented in previous studies.^{180,181} Likewise, a previous study¹⁸² documented the potential of carrot peel waste for the bioconversion of pectin and carotene through advanced biorefinery approaches. In addition, another study¹⁸³ demonstrated the conversion of greenhouse horticultural waste into value-added products through bioconversion and biorefinery approaches. These approaches can effectively valorize the unavoidable yet potential food waste and waste streams through the concept of bioeconomy. However, a recent study in Singapore reported the potential of HW for bioconversion into biochar through gasification strategies.¹⁸⁴ In the biorefinery approach, HW biomass can be converted into bioenergy or biofuels through various approaches, including acidogenesis, solventogenesis, fermentation, microbial bioconversion, and electrolysis.^{185,186} Microbial fuel cells have the ability to produce bioelectricity by oxidizing organic chemicals. On the other hand, bioplastics can be generated by fermenting or bioconverting fruit and vegetable wastes that are abundant in lignin and other fibers. Microorganisms or enzymes can be utilized to decompose the complicated organic compounds into simpler molecules such as sugars, which can subsequently be subjected to additional processing to produce sustainable bioplastics.^{125,130}

Numerous studies have reported sole biorefinery approaches for the efficient bioconversion of HW into value-added energy or fuels.^{180,181,187} However, owing to cost-effectiveness, incomplete bioconversion, and sustainability for large-scale applications, these single biorefineries are not suitable. Thus, an integrated biorefinery will open a new research area to solve this problem during the holistic and cost-effective integrated management of fruit and vegetable wastes.^{99,133,187} An integrated biorefinery coupled with green extraction approaches will enhance the bioeconomy through the sustainable circular economy of horticultural waste valorization.^{33,138,143,150,188}

8. Immobilized enzymes for food waste conversion

Food waste valorization is an attempt to convert discarded waste materials into valuable products such as biopolymers, biofuels, and biocompounds. Numerous advanced chemical and microbial extractions of valuable biopolymers from different food waste streams have been reviewed.⁷² However, both free and immobilized enzymes have been reported to convert food waste into valuable bioactive molecules as alternatives to conventional methods of food waste valorization.^{189,190} Utilizing immobilized enzymes in food waste valorization presents multiple advantages, including operational stability, reusability, and resilience to temperature and pH fluctuations. These attributes enhance the efficiency and effectiveness of bioconversion processes for food waste streams.^{174,175} The industrial application of various immobilized enzymes was documented for application lenience over free enzymes. To enhance the efficient conversion of organic waste



Table 2 The conversion of value-added products from horticulture waste

Food processing sector	Types of food waste	Products	Conversion techniques	Application	Ref.
Fruit and vegetables processing sector	Peels, pulp, pomace, stalks, leaves, seeds, cores, unharvested parts, spoiled and damaged parts	Polyphenols, organic acids, carotenoids, anthocyanin, flavonoids, dietary fibers, tocopherol, vitamins, aeromantic compounds, phytochemicals, stilbenes, lignans, pectin, cellulose, nutrients (N, P, K)	Drying, solid-state fermentation, solvent extraction, ultrasound, enzyme and microwave-assisted extraction, pressurized liquid extraction, supercritical CO ₂ extractions, aerobic digestion, and composting	Food fortification Enhance nutritional value and oxidative stability Novel functional food ingredients Extracted oils in the cosmetics and food industries Promote the growth and development of cells production of probiotics, food additives, flavor enhancers, chewing gum, and stabilizers for oil-water emulsions Nutraceuticals, functional foods, baked goods such as muffins and brownies, as well as packaging materials Biodegradable and edible plastics Enzyme production, cancer prevention, cardio, and digestive disease prevention Production of biogas, animal feed, fertilizer, organic acids, enzymes, and bioactive compounds	153-159
Dairy industry	Dairy processing water, dairy sludge & effluent, whey, dissolved organic compounds, lipids, carbohydrates, and organic substances	Whey and whey permeate, bio-plastics, biofuels, bioenergy, organic acids, peptides	Physicochemical treatment, micro- and nano-filtration, aerobic and anaerobic digestion, advanced biotechnological processes, coagulation, fermentation, aerated lagoons	Production of functional food, emulsifier, single-cell protein, polysaccharides, lipase, citric acid, lactic acid, propionic acid, xanthan gum, whey protein isolate, polyhydroxyalkanoates, polyhydroxybutyrate, alcoholic beverages, ethanol	160-165
Animal products processing	Skin, blood, gut, horns, bones, liver, lung, kidney, tendons, brains, spleen, and internal organs, poultry feather	Nutrients, fiber, energy, meat powder, peptides or biopeptides, collagen, essential amino acids, saturated and unsaturated fatty acids, biodiesel, fibreboard, bioplastic films	Solid state fermentation (SSF), enzymatic & non-enzymatic hydrolysis, aerobic digestion, chemical treatment, water extraction, mincing, concentration, colloid milling, homogeneity, and spray drying	Utilization as animal feed, biodiesel, or biogas production, the development of dietetic items such as chitosan, the extraction of natural colors, and the incorporation of collagen into cosmetics It is a highly valuable reservoir of many essential trace minerals The potential applications of this substance include its use as a protein supplement, a feasible alternative to milk, a supplementary source of lysine, and a stabilizer for vitamins	166-169



Table 2 (Contd.)

Food processing sector	Types of food waste	Products	Conversion techniques	Application	Ref.
Fish, seafood, seaweed processing	Scale, bone, muscle, liver, gut, head, blood skin, processing water seaweed, oyster and crustaceans' shells	Protein, peptide, collagen, gelatin, chitin and chitosan, alginate, agar, and carrageenan, fish meal, fish oil, fertilizer/manure, fish silage, fish sauce	Solid state fermentation (SSF), enzymatic hydrolysis, chemical treatment	The production of functional foods, nutraceuticals, antifreeze compounds, surimi, fish protein hydrolysates, fish protein concentrates, fish enzymes, gelatin, collagen, carotenoids, chitin, chitosan, glucosamine, and fermented fish products is undertaken in the manufacturing industry	170–174

into valuable products, researchers have explored various immobilization techniques, including physical adsorption, entrapment, covalent bonding, and crosslinking. These methods have been applied using diverse support media such as alginate, glass beads, agar, and clay minerals.^{190,191} The food waste stream is a rich source of diverse carbohydrates including polysaccharides and disaccharides. Carbohydrates derived from the food waste stream can be effectively converted to bioactive galactosides through the immobilized enzyme β -galactosidase on a suitable nanocatalytic support surface.¹⁹² The novel enzyme β -galactosidase, derived from different microbial strains, can also serve as an immobilized enzyme when paired with an appropriate support surface. This combination enables

the synthesis of a wide range of disaccharides from dairy-waste materials.¹⁸⁹ Similarly, pectin is one of the most important carbohydrates derived from vegetable waste streams. Pectin synthesis was facilitated using an immobilized pectin-degrading enzyme (derived from *Bacillus licheniformis*) on agar-agar support media.¹⁹³ Immobilized enzyme-based pectin synthesis is a sustainable approach over other conventional chemical techniques owing to the low cost and reusability of enzyme immobilization Fig. 4.

Chitin is a major carbohydrate in fish and crustacean waste streams. The dual reactor-based uninterrupted production of chitosan-based chito-oligosaccharides by an oligosaccharide-synthesizing enzyme immobilized on support media was

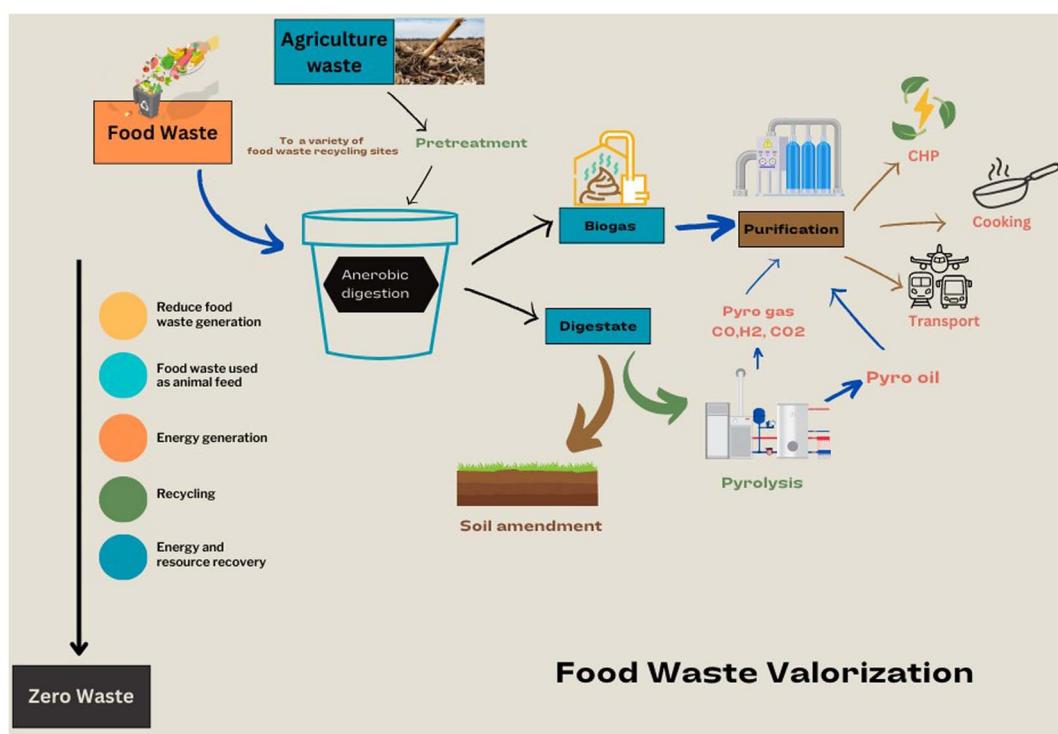


Fig. 4 An updated valorization approach, including the integrated biorefinery for the sustainable recycling of food waste and agro-food wastes toward the zero waste campaign.



documented.¹⁹⁴ The selection of support media depends on the enzyme sources, enzyme-binding sites, and adsorption capacity of the support media. A better combination of support media and enzymes may lead to sustainable and economical synthesis of bioactive compounds from organic food waste.^{191–193} In the management of industrial waste, the use of cost-effective and adsorptive support surfaces, along with the reusability of immobilized ligninolytic enzymes, has been identified as an emerging and innovative technological approach.¹⁹⁵ The immobilization process is advantageous because of the diverse tolerance of pH, temperature, and storage conditions of enzymes for enhanced and sustainable application for tackling food waste management.^{191,194} However, biodiesel production from the industrial food waste stream (oil, fat, and greases) is rendered by lipase. A previous study explored the potential of nanotechnology by utilizing lipase immobilization on carbon nanotubes for sustainable and continuous biodiesel synthesis from crude vegetable oil.¹⁹⁶ In a pioneering investigation, the cost-effective and highly efficient catalytic potential of vegetable oil waste was observed in biodiesel production. This was achieved by immobilizing lipase on dendrimer-coated magnetic carbon nanotubes.¹⁹⁷ Therefore, the immobilization of enzymes has become an attractive option over other conventional chemical and microbial approaches owing to their robustness, economic feasibility, and environmental sustainability for the potential management of food waste streams into valuable bioactive compounds Fig. 5.

9. Industrial food waste valorization for tackling waste streams

In the food industry context, “food industrial wastes” most often refer to sections of leftovers produced as a result of food manufacturing processes. They are composed of a broad array

of organic components that are discarded after production. Industrial food waste collected from diverse sectors, including fruit and vegetable processing, oil processing, paper manufacturing, and dairy processing industries, represents a potential substrate for the bioprocessing of a wide variety of products. These products include pigments, enzymes, acids, biofuels, bioactive agents, and biopolymers, with applications spanning the industrial and therapeutic domains.

A comprehensive list of industrial food waste valorization and the sustainable conversion of waste into wealth is listed in Table 3.

10. Future opportunities and challenges

Sustainable management of food waste (FW), including horticultural waste (HW) and domestic kitchen waste, through bioconversion and biorefineries, has emerged as a potential technique. However, according to previous studies, several research uncertainties still exist as barriers to the sustainable conversion of FW into value-added products. Establishing an industrial biorefinery for the bioconversion of food waste into valuable compounds is a major challenge related to sustainability, cost-effectiveness, environmental considerations, and technological obstacles. The design and implementation of industrial biorefinery plants and bioreactors are currently in the early stages of research and development. Alternatively, several pilot experiments are ongoing, but a cost-benefit analysis has not yet been performed. As a result, pilot-phase biorefineries have been identified as potential alternatives for sustainable handling of food waste. However, assurance of industrial and commercial sustainability has not yet been confirmed. Therefore, the integration of a comprehensive biorefinery could offer a comprehensive solution to address the current challenges associated with the sustainable management of hazardous waste (HW), utilizing biorefinery and circular economic principles. Conversely, previous research has documented several emerging extraction technologies and methodologies designed to extract valuable products from both industrial and household food waste and waste streams, holding potential for value-added applications.

However, green extraction approaches and sustainable integrated biorefineries have yet to be investigated. Therefore, meticulous adaptive and pilot studies must be conducted to establish a sustainable and effective biorefinery for extracting value-added products and bioenergy through a circular economy using fruit and vegetable wastes.

In contrast, food waste recycling and management were not separated but included municipal waste management in developing countries.^{49,213} Thus, there is scope for waste separation and further valorization of food waste in developing countries. In particular, kitchen and industrial wastes are poorly managed because of insufficient technical knowledge and research data. Poor food waste management can create several environmental pollutants, including greenhouse gases and toxic environmental contaminants (e.g., toxic metals and pesticides). Although the

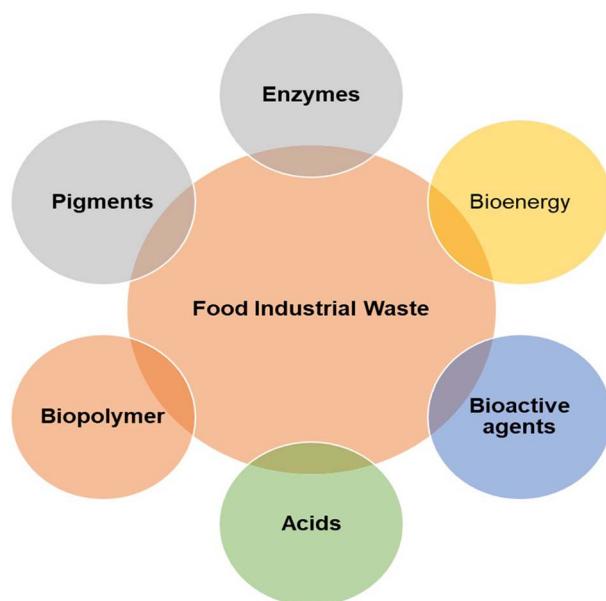


Fig. 5 An overview of the industrial food waste valorization into value added products.



Table 3 The valorization of food waste, especially industrial food waste, to value-added products through microbial strains

Products categories	Products	Food industrial waste	Microorganism	Process	Ref.
Pigments	Carotenoids	Rice powder	<i>Bacillus clausii</i>	Solid state fermentation	197–203
	Lycopene	Soybean meal	<i>Rhodopseudomonas faecalis</i>	Solid state fermentation	
	Phycocyanin	Sugarcane vinasse	<i>Aphanothecace microscopic</i>	—	
	Prodigiosin	Cassava wastewater	<i>Serratia marcescens</i> UCP 1549	—	
	Red pigment	Corn cob	<i>Monascus purpureus</i> KACC 42430	Solid state fermentation	
Enzymes	Lycopene	Tomato peel and seeds	—	Supercritical CO ₂ extraction	
	Cellulase	Lignocellulosic biomass	<i>Pleurotus ostreatus</i>	Solid state fermentation	203–206
	Pectinase	Lemon peel pomace	<i>Aspergillus niger</i>	Solid state fermentation	
	Protease	Pulse flour, corn, vegetable pills, gram husk	<i>Nocardiopsis alba</i> OM-4	Solid state fermentation	
Bioactive agents	Lipase	Rape seed oil	<i>Aspergillus</i> sp. DPUA 1727	Solid state fermentation	
	Xylanase	Liquefied wheat bran	<i>Aspergillus niger</i>	Submerged fermentation	
	Phenolic compounds	Pineapple waste	<i>Kluyveromyces marxianus</i> NRRL Y-8281	Solid state fermentation	207–211
	Phenolic compounds	Fig by-products using Rice bran	<i>Aspergillus niger</i> HT4	Solid state fermentation	
	Gallic acid and ferulic acid	Soybean meals	<i>Rizopus oryzae</i>	Solid state fermentation	
Biopolymer	Caffeic acid, naringenin, daidzein		—	Microwave-assisted extraction	
	Ellagitannins, punicalagin, and punicalin	Pomegranate peels	—	Ultrasound-assisted extraction	
	Chitosan	Corn steep liquor	<i>Rhizopus arrhizus</i> UCP 402	Fermentation	212
Acids	Pectin	Jackfruit peel	—	Sonication microwave synergistic extraction	213
	Lactic acid	Mango peels	<i>Lactobacillus casei</i>	Hydrolyzed steam explosion	214
Bioenergy	Propionic acid	Cheese whey	<i>Propionibacterium acidipropionici</i>	—	215
	Fumaric acid	Food waste	<i>Rhizopus oryzae</i>	Hydrolyzed	216
	Biodiesel	Waste cooking olive oil	<i>Aspergillus niger</i>	Fermentation	213–216
	Bioethanol	Sugarcane bagasse	<i>Saccharomyces cerevisiae</i>	Solid state fermentation	
	Bioethanol	Rice straw	<i>Saccharomyces cerevisiae</i>	Fermentation	

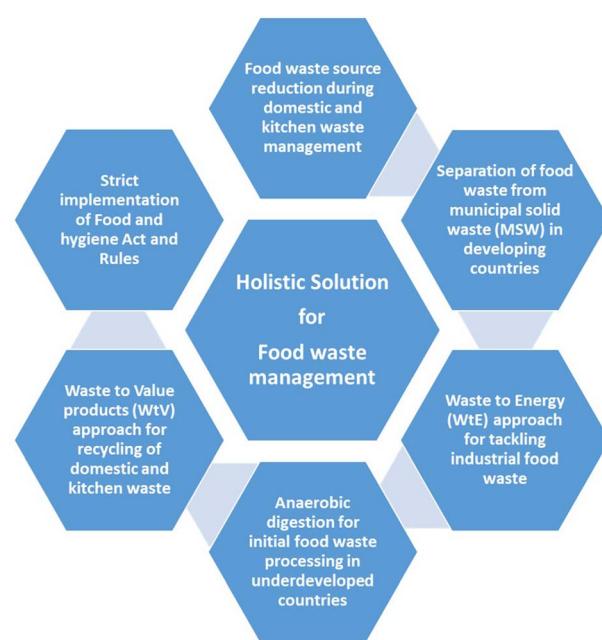


Fig. 6 A policy advocacy and holistic recommendation concerning further opportunities regarding food waste management including advanced valorization and strict enforcement of rules and regulations.

thermal processing of FW (incineration) and biochemical processing (anaerobic digestion) is a well-adopted valorization or management process to tackle industrial and domestic food waste, the sustainable and green extraction of food waste for bioactive molecules is still in the pilot phase. Thus, establishing integrated and sustainable valorization approaches, including biorefinery, is a promising option for recycling and managing industrial and domestic food waste. The following recommendations were suggested for the effective and sustainable management of global food waste (Fig. 6):

(1) Minimizing waste generation during kitchen food processing and domestic use can be achieved through source reduction. This approach designates unavoidable waste materials, including potato and carrot peels, citrus rinds, and pomace fruits, as food waste. Consequently, a substantial portion of the food waste generated during food processing and cooking can be effectively managed through source reduction practices.

(2) Separating food waste from municipal solid waste is a vital step, particularly in populous nations, where food waste is often disposed of together with other waste. This practice is essential for efficient food waste management in unplanned disposal settings, which are common in various Asian and African countries.



(3) Recent years have seen the adoption of advanced and sustainable approaches, broadly categorized as (a) Waste to Energy (WtE) and (b) Waste to Value product (WtV). These multifaceted processes aim to recycle and convert food waste into valuable resources and present viable options for exploration on a global scale, including the local food industry.

(4) Finally, anaerobic digestion should be implemented to tackle the bulk of unavoidable food waste on the municipal pilot and industrial scales *via* the strict enforcement of global acts and rules concerning food waste recycling and sustainable management.

11. Conclusion

In summary, food waste valorization (FWV) is a promising sustainable approach for addressing global food waste and its conversion into value-added products. Food waste (FW) is generally derived from domestic or industrial waste streams. Despite the valuable sources of bioactive molecules, food waste (FW) and waste streams have been underexplored for sustainable conversion owing to a lack of awareness and comprehensive research efforts. Although developed countries and giant food companies are concerned about sustainable recycling and converting FW into wealth through various contemporary valorization approaches, FWV is limited in global scale and small-scale food industries. Therefore, a large portion of FW remains untouched and can be dumped with municipal solid waste. As a result, FW has become a global concern because of the unplanned management of other solid waste. The inherent feature of FW is mediated by anaerobic digestion, which leads to odorous waste instead of the sustainable conversion from waste to wealth. In this critical appraisal, we suggested a hypothetical waste pyramid to scrutinize the most preferable options for the sustainable conversion of global food waste. The integrated bio-refinery is a promising option for industrial food waste management. Domestic and kitchen wastes should be managed separately with the initiative of waste separation from municipal solid waste. Traditionally, food waste has not been studied because of its potential as a resource recovery feedstock. However, several studies have suggested that diversified food waste is a potential, yet untapped source of bioactive molecules and bioenergy. Thus, an advanced valorization process can extract or convert value products from food waste. The integration of life cycle assessment (LCA) and hydrothermal conversion (HTC) plays a vital role in optimizing the overall output from waste streams. Advanced research is also in the initial stages of pilot experiments. Thus, further combined and adaptive research and scale-up of existing pilot studies should be explored toward meeting the UN's sustainable development goals (SDGs). Finally, the adoption of an advanced and sustainable valorization approach can significantly contribute to promoting a circular bioeconomy, effectively addressing the global macro issue of food waste.

Author contributions

Conceptualization; writing the draft: Aniruddha Sarker, Raju Ahmed; writing and reviewing, data curation: S. M. Ahsan, Juwel Rana, Mithun Kumar Ghosh, and Rakhi Nandi.

Conflicts of interest

"There are no conflicts to declare".

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