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Review Article

Food waste valorization for resource recovery and biorefinery solutions: novel technologies, separation processes and technoeconomic analysis

Prakash Kumar Sarangi[1*], Thangjam Anand Singh[1], Ng. Joykumar Singh[1], Kalyani Sharma[2], Rajesh Kumar Srivastava[3], Akhilesh Kumar Singh[4], Harikesh B Singh[5], Uttam Kumar Sahoo[6], Sanjukta Subudhi[7], Govindaraj Kamalam Dinesh[8], Vinod V. T. Padil[9]

[1]AICRP on PHET, College of Agriculture, Iroisemba, Central Agricultural University, Imphal-795004, Manipur, India.
[2]College of Horticulture and Forestry, Central Agricultural University, Passighat, Arunachal Pradesh, India.
[3]Department of Biotechnology, GIT, Gandhi Institute of Technology and Management (GITAM) Visakhapatnam, India, 530045.
[4]Department of Biotechnology, School of Life Sciences, Mahatma Gandhi Central University, Motihari, Bihar - 845 401, India.
[5]Department of Agriculture, Integral Institute of Agricultural Science and Technology, Lucknow-226026, India.
[6]Department of Forestry, Mizoram University, Aizawl - 796 004, India.
[7]Microbial Biofuels & Bio-chemicals Area, TERI Center of Excellence on Biochemicals, Advanced Biofuels Division, The Energy and Resources Institute (TERI), New Delhi, India.
[8]Department of Biochemistry, Physiology, Microbiology and Environmental Science, College of Agriculture, Iroisemba, Central Agricultural University, Imphal - 795 004, Manipur, India.
[9]School of Nanoscience, Central University of Gujarat, Baroda, India.

[*]**Correspondence**
Prakash Kumar Sarangi
sarangi77@yahoo.co.in

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Background: Food Waste Valorization (FWV) stands as a pivotal strategic approach for addressing the pervasive global issue of food waste, concurrently presenting a sustainable remedy for resource recuperation. Conventional disposal methodologies, such as landfilling and incineration, undergo critical scrutiny for their ecological ramifications, setting the foundation for an exhaustive exploration of inventive FWV methodologies.

Methods: This all-encompassing analysis delves into cutting-edge technologies and innovative separation processes meticulously crafted to enhance the valorization of food waste. The examination amalgamates advancements in crucial FWV technologies, including anaerobic digestion, composting, and pyrolysis, accentuating their effectiveness in transforming food waste into valuable commodities like biogas, compost, and biochar. Furthermore, the study scrutinizes emerging techniques like microbial fermentation, enzymatic hydrolysis, and insect-based conversion, offering valuable insights into their potential for large-scale resource recovery. Integral to the success of FWV initiatives are state-of-the-art separation processes, and this analysis evaluates avant-garde methods such as membrane filtration, chromatography, magnetic separation, supercritical fluid extraction, and electrostatic separation. This paper highlights implementations of FWV technologies and distinguishes laboratory, pilot and full-scale evidence. The scope is restricted to food waste, food-processing by-products and food-processing effluents, and the literature was identified through a structured search covering 2015-2026.

Results: These processes play a pivotal role in extracting high-quality resources efficiently from food waste, ensuring the economic feasibility and environmental sustainability of FWV endeavors. Techno-economic and life-cycle indicators reported specifically for food-waste systems are compared, an integrated feedstock-to-residue biorefinery framework is proposed, and specific research gaps and priorities are identified.

Conclusion: Thus, it furnishes a comprehensive portrayal of the present landscape, contributing to the scientific dialogue on sustainable food waste management practices and resource recovery.

Keywords: *food waste, resources, biochemicals, bioenergy, valorization, separation technique*

Introduction

Food waste represents a substantial challenge on a global scale, with far-reaching implications for the environment, economy, and societal well-being. The magnitude of this issue is starkly evident, as approximately one-third of all food produced for human consumption, equating to 1.3 billion tons annually, is either lost or wasted (Sarangi et al., 2023; FAO, 2011). More recent estimates indicate that 1.05 billion tonnes of food waste, including inedible parts, were generated at retail, food-service and household levels in 2022, of which households accounted for 60% (UNEP, 2024). With the world's population projected to reach 9.7 billion by 2050 (UN, 2019), the imperative to find sustainable solutions for mitigating food waste is more pressing than ever. Conventional methods of dealing with food waste, including landfilling and incineration, have proven to be inadequate and environmentally harmful. Landfilling, in particular, results in methane production, potent greenhouse gas, through anaerobic decomposition. Incineration, on the other hand, poses challenges related to air pollution and lacks the potential for resource recovery (Talan et al., 2021). Against this backdrop, the concept of Food Waste Valorization (FWV) emerges as a transformative approach, aiming not only to alleviate the environmental impact of food waste but also to extract valuable resources from discarded materials. The urgency surrounding food waste is underscored by its profound environmental consequences, notably the generation of methane in landfills. This contributes significantly to climate change, amplifying the carbon footprint associated with food production and disposal (Devi et al., 2023). By redirecting these wasted resources back into the production cycle, FWV offers a tangible means of mitigating these adverse effects and fostering more sustainable and resilient food systems. FWV represents a paradigm shift, treating food waste not merely as a problem but as a valuable resource with untapped potential. Aligned with the principles of a circular economy, FWV seeks to minimize waste and maximize resource utilization through recycling, reusing, and recovering. The valorization process involves the conversion of food waste into useful products, energy, or materials, thereby closing the loop in the food supply chain (Kannah et al., 2020). The efficiency of food production is pegged at 50%, translating to the loss or non-utilization of roughly 1.6 billion tons of food raw material (Said et al., 2023). The United Nations has incorporated sustainable consumption and production as one of the key objectives among their 17 Sustainable Development Goals (SDGs) (UN, 2015). This approach not only addresses the environmental impact of food waste but also presents economic opportunities by creating new revenue streams and reducing disposal costs. This comprehensive review aims to explore the landscape of FWV emphasizing the technologies and novel separation processes integral to resource recovery. It encompasses diverse stages of the food supply chain, addressing the various forms and compositions of food waste. This review will examine conventional methods of food waste disposal and their limitations, paving the way for an in-depth exploration of emerging FWV technologies (Kathi et al., 2023). Conventional methods, such as anaerobic digestion, composting, and pyrolysis, will be scrutinized alongside novel approaches like microbial fermentation, enzymatic hydrolysis, and insect-based conversion. The role of separation processes, including membrane filtration, chromatography, magnetic separation, supercritical fluid extraction, and electrostatic separation, in enhancing resource recovery will be critically evaluated. In exploring FWV technologies, anaerobic digestion stands out as a key process. This biological method involves the breakdown of organic materials in the absence of oxygen, leading to the production of biogas and nutrient-rich digestate (Pal & Tiwari, 2023; Wong et al., 2023). The effectiveness of FWV often hinges on the efficiency of separation processes. Membrane filtration techniques, such as ultrafiltration and nanofiltration, enable the concentration of valuable compounds from food waste. Magnetic separation is a process using magnetic fields to separate materials, facilitating recycling and reducing the environmental impact of waste disposal. Supercritical fluid extraction utilizes supercritical fluids to extract specific compounds from solid matrices, offering a solvent-free and selective approach for recovering bioactive compounds from food waste. Electrostatic separation exploits differences in the electrical properties of particles to separate them based on their charge (Somorin et al., 2023). This technique has been investigated for its potential in recovering plastics and other materials from mixed waste streams, enhancing recycling efficiency. Challenges in FWV persist, including regulatory barriers, public perceptions, and technological limitations. Interdisciplinary collaborations, policy support, and ongoing research are deemed essential to overcome these challenges and foster the widespread adoption of sustainable FWV practices. The review will also address existing challenges in the field and provide insights into future perspectives. Emphasis will be placed on the need for interdisciplinary collaborations, policy support, and ongoing research to facilitate the widespread adoption of sustainable FWV practices. This review seeks to contribute to the scientific discourse surrounding Food Waste Valorization by offering a comprehensive overview of the technologies and separation processes driving resource recovery which are not critically described before with novel technologies. By shedding light on the advancements,

challenges, and opportunities within this evolving field, it aims to inspire further research and innovation towards a more sustainable and circular approach to managing food waste globally (Figure.1).

Scope and definition

In this review, food waste (FW) denotes food and associated inedible parts removed from the food supply chain at retail, food-service and household levels, consistent with the UNEP Food Waste Index definition (UNEP, 2024). Food-processing by-products are solid residues generated during industrial food processing (for example, fruit pomace and peels, cheese whey, fish and seafood processing residues and bakery returns), and food-processing effluents are liquid streams from food manufacturing that carry recoverable proteins, lipids and sugars (Lee & Stuckey, 2022). Agricultural crop residues (for example, cereal straws, husks and stover), forestry residues and effluents from non-food industries are outside the scope of this review. Studies on such feedstocks are cited only where a separation or process principle is explicitly discussed as transferable to food-waste streams, and these citations are identified as transferable in the text and in Table 3.

Review methodology

This article is a narrative review supported by a structured literature search; it is not a systematic review. Searches were run on 8 October 2026 in Europe PMC (which indexes MEDLINE/PubMed, PubMed Central and Agricola records) for publications from 2015 to 2026. Feedstock terms ("food waste", "food processing waste", "food by-product", "whey", "pomace", "fruit and vegetable waste") were combined with conversion terms (anaerobic digestion, fermentation, pyrolysis, hydrothermal carbonization, black soldier fly, single cell protein, polyhydroxyalkanoate), separation terms (membrane, ultrafiltration, nanofiltration, electrodialysis, pervaporation, supercritical, adsorption, gas stripping), economic terms (techno-economic, economic feasibility, net present value, payback) and environmental terms (life cycle assessment, global warming potential); these four searches returned 3,335, 1,680, 191 and 250 records, respectively, before de-duplication (Supplementary Table S1). Studies were retained when they used food waste, a food-processing by-product or a food-processing effluent as feedstock (or explicitly evaluated a separation principle transferable to such streams), reported at least one quantitative outcome (yield, recovery, purity, energy demand, cost or environmental indicator) and were peer-reviewed; earlier studies were retained only where they provide full-scale or foundational measurements, and retracted articles were excluded. Each study was classified by the scale of its evidence as laboratory, pilot, full-scale or model-based (process simulation or techno-economic modelling). Scopus and Web of Science were not searched, which is a limitation of the literature selection.

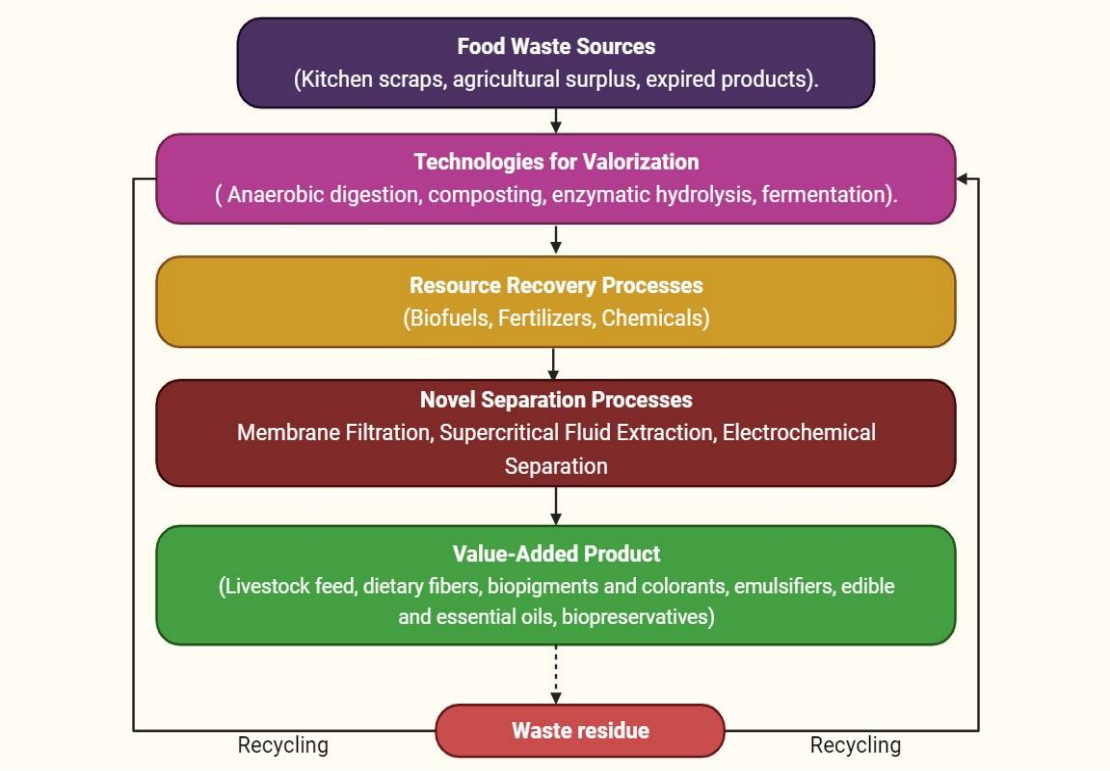


Figure. 1 Wastes and novel production with separation technology for high purity products.

Source of food waste

Food waste is a global predicament that manifests at every stage of the food supply chain, culminating in significant environmental, economic, and social repercussions. Understanding the intricate sources of this waste is paramount to developing comprehensive strategies that can tackle the issue holistically. From the fields of agricultural production to the dining tables of consumers, each stage contributes to the staggering amount of food discarded annually. Furthermore, a statistical compilation of food-waste characteristics from 70 studies reported a mean carbohydrate content of 36.4% of volatile solids (VS) and a mean pH of 5.1, and found that 24% of the variation in food-waste characteristics was explained by geographical origin, collection source and season (Fisgativa et al., 2016). This article delves into the multifaceted origins of food waste, exploring the intricacies of overproduction, quality standards, processing and manufacturing practices, distribution and retail challenges, consumer behavior, and the post-consumer disposal phase. At the agricultural production stage, overproduction is a prominent source of food waste. Farmers, facing uncertainties in market demand, weather conditions, and yield predictions, often cultivate more than is required. Surpluses result in crops being left unharvested or discarded, leading to a significant loss of resources (Chhandama et al., 2022). Additionally, stringent quality standards, both set by retailers and driven by consumer preferences, contribute to food waste in agriculture. Fruits and vegetables that do not meet cosmetic standards are often rejected, creating a scenario where perfectly edible produce is discarded based on appearance, contributing to significant losses. Moving into the processing and manufacturing stages, the trimming and removal of certain parts of raw materials are notable contributors to food waste. During processing, vegetable peels, fruit skins, and animal by-products are often discarded. While some of these by-products find alternative uses, a considerable portion still ends up as waste (Lee & Stuckey, 2022). Overordering of raw materials in the industrial food processing sector is another significant issue. The desire for consistent production often leads to surplus raw materials, which may be discarded due to changes in product formulations or unexpected fluctuations in demand. Short shelf-life products, particularly perishable goods like dairy, baked goods, and fresh produce, contribute to food waste during distribution and retail. Inefficiencies in distribution, inventory management, and logistics can result in the disposal of products that have surpassed their expiration dates. Overstocking and the presence of unsold inventory further contribute to waste, as retailers often order excess quantities to meet consumer demand, leading to surplus inventory that may not be sold before reaching its expiration date (Kannah et al., 2020). Inadequate storage and handling practices at both the distribution and retail levels can accelerate food spoilage and waste. Poor temperature control, improper handling of perishable items, and unsuitable storage conditions contribute to the deterioration of food products, leading to their disposal. Additionally, aesthetic standards continue to play a role in contributing to food waste at the retail level. Products that do not meet specific visual criteria, even if safe for consumption, may be removed from shelves prematurely, exacerbating the issue. Consumer behavior represents a critical source of food waste. Over-purchasing, influenced by bulk discounts, sales promotions, and a lack of meal planning, leads to excess food that often goes uneaten and eventually becomes waste. Confusion and misinterpretation of date labels also contribute to consumer-driven food waste. Labels such as "sell by," "use by," and "best before" are often misunderstood, leading consumers to discard products that are still safe to eat (Nayak & Bhushan, 2019). Plate waste is a common source of food waste at the consumption stage. Consumers may prepare or order more food than they can consume, and uneaten portions are discarded. In households, this can result from cooking larger quantities than needed, while in restaurants, it may stem from oversized portions. Even after reaching the consumer, food waste persists in the post-consumer stage. The lack of infrastructure for food recovery, including composting and anaerobic digestion facilities, contributes to the disposal of food that could otherwise be diverted from landfills. Consumer disposal practices also play a critical role in post-consumer food waste. In regions where convenient disposal options, such as composting or food waste bins, are lacking, consumers are more likely to discard food in regular trash bins. Cultural attitudes towards food and perceptions of abundance can influence consumer behavior and contribute to food waste. In societies where abundance is synonymous with prosperity, the inclination to discard food that is perceived as less fresh or less appealing is higher (Capanoglu et al., 2022). Addressing food waste requires a holistic approach that spans the entire supply chain and involves stakeholders at each stage. Precision farming practices, relaxed quality standards, and efficient inventory management are critical in the agricultural phase. In processing and manufacturing, exploring innovative uses for by-products and improving inventory management can minimize waste. Distribution and retail can benefit from improved supply chain logistics and enhanced education on date labels. Consumer behavior can be influenced by raising awareness about the environmental and economic impacts of food waste. Post-consumer stages require investment in infrastructure for food recovery and the introduction of convenient disposal options. Policies and regulations that incentivize businesses to reduce food waste and technological innovations, such as smart packaging, can further contribute to addressing this global challenge (Lytras et al., 2021). Precision farming practices can help optimize crop yields and reduce overproduction in agriculture. Adopting precision farming techniques, such as precision irrigation and the use of drones for crop monitoring, allows for a more targeted and efficient approach to agriculture. Relaxing quality standards for cosmetic appearance in agriculture can also mitigate food waste. Educating consumers about the natural variations in appearance of fruits and vegetables and promoting the consumption of "imperfect" produce can help reduce the rejection of perfectly edible items based on aesthetic criteria. Initiatives that highlight the

nutritional value and taste of these products can shift consumer perceptions and reduce the demand for visually uniform produce (Thygesen et al., 2021). In conclusion, addressing food waste requires a comprehensive and collaborative approach that involves stakeholders at every stage of the supply chain. By implementing targeted interventions, fostering awareness, and embracing technological innovations, it is possible to mitigate the impact of food waste and transition toward a more sustainable and efficient food system. The intricate sources of food waste present opportunities for innovation, education, and policy development, ultimately contributing to a more responsible and resilient global food system.



Figure 2. Different sources of food waste generation.

Promoting sustainable agriculture

Food-waste streams differ markedly in composition, and these differences determine which valorization routes are technically suitable (Table 1). Mixed household and food-service FW is carbohydrate-rich and acidic, which predisposes anaerobic digesters to rapid acidification; FW collected with green waste has high dry matter and ammonia contents, FW from the organic fraction of municipal solid waste has high cellulose, and FW from Asia has high ammonia and sodium contents (Fisgativa et al., 2016). Mixed FW also contains extractable oil, reported at 14.15% (w/w) in one integrated study (Patel et al., 2019). Cheese whey retains around 50% of milk solids, with lactose at 66-77%, proteins at 8-15% and mineral salts at 7-15% of dry matter, as compiled by Lappa et al. (2019). Fish by-products contain 49.22-57.92% protein, 21.79-30.16% ash and 7.16-19.10% fat on a dry-weight basis, as compiled by Coppola et al., 2021. Bread waste is a starchy material that supplies easily extractable fermentable sugars without the harsh pretreatment, and associated inhibitor formation, required for lignocellulosic feedstocks (Narisetty et al., 2021). Fruit and vegetable wastes are perishable and heterogeneous, which creates logistical constraints and favours extraction of bioactive compounds, enzymes, bioplastics and biofuels according to composition and market demand (Esparza et al., 2020).

Food waste and resource recovery

Food waste is a pervasive issue, seeping through every stage of the supply chain from cultivation to consumption (Wong et al., 2023). This wastefulness not only has far-reaching environmental consequences, contributing to greenhouse gas emissions and resource depletion, but also inflicts economic losses on producers, businesses, and consumers. The social ramifications are equally profound, with millions facing food insecurity amid the abundance of discarded edible food. Resource recovery addresses this problem. It involves extracting value from discarded food, transforming it from an environmental burden into a reservoir of potential resources. Pyrolysis involves the high-temperature decomposition of organic materials (Trivedi et al., 2020). It converts food waste into biochar for soil enrichment and syngas, a potential fuel source, illustrating the transformative power of technology. Black soldier fly larvae bioconvert organic waste into protein-rich biomass and nutrient-rich frass. This illustrates the potential of insect-based conversion as a sustainable solution, still in the experimental phases but hinting at a transformative future. Microbial fermentation and enzymatic hydrolysis utilize microorganisms or enzymes to break down complex organic compounds in food waste. The resulting composition includes bioethanol, a renewable fuel, and other valuable biochemicals. Complementing these resource recovery technologies are novel separation processes, enhancing the efficiency of resource extraction. Membrane filtration techniques utilize semi-permeable membranes to separate components based on size, contributing to the concentration of valuable compounds from food waste. Chromatography, a separation technique employing a stationary

phase and a mobile phase, enables the isolation of specific compounds from food waste, contributing to the production of high-purity products. Magnetic separation retrieves metals from food waste, promoting recycling efficiency. Supercritical fluid extraction utilizes supercritical fluids like carbon dioxide to extract specific compounds from solid matrices. Electrostatic separation exploits differences in the electrical properties of particles to separate materials based on their charge. Investigated for its potential in recovering plastics and other materials from mixed waste streams, this technique enhances recycling efficiency and reduces the environmental impact of waste disposal. Regulatory barriers, public perceptions and technological limitations remain. Regulations governing waste management practices vary globally, posing challenges for the widespread adoption of certain technologies. Public perceptions surrounding imperfect produce and the acceptability of insect-based conversion demand nuanced conversations to overcome societal hesitations (Ho & Chu, 2019). Technological limitations, especially in regions with limited infrastructure, present barriers to implementing resource recovery technologies at scale. The upfront costs and complexities associated with certain processes, such as pyrolysis or advanced separation techniques, may hinder adoption, calling for continued research and innovation to refine these technologies and make them more accessible. Innovations in technology, business models, and policy frameworks are essential to address existing challenges. The development of more cost-effective and user-friendly resource recovery technologies can pave the way for broader implementation (Dou & Toth, 2021).

Bioenergy

Food waste is recognized as an abundant and promising feedstock for bioenergy production due to substantial concentrations of carbohydrate-rich polymers and other biodegradable organic compounds making suitable for microbial bioconversion processes (Sen et al., 2016). The conversion of food waste into bioenergy simultaneously contributes to sustainable waste management as well as mitigating greenhouse gas emissions through the replacement of fossil-based energy resources with renewable bioenergy (Galanakis, 2020). The successful valorization of food waste into bioethanol largely depends on substrate composition and the availability of nutrients required for microbial growth and metabolism. Overall, the conversion of food waste into bioenergy provides an integrated strategy for addressing the dual challenges of organic waste management and sustainable energy production. Consequently, the effective valorization of food waste has the potential to contribute to circular bioeconomy development, climate change mitigation and resource efficiency. Table 2 summarises comparison, and gives the corresponding techno-economic and life-cycle indicators.

Biogas

Biogas is a renewable energy source generated through the anaerobic digestion of organic materials, such as food waste, agricultural residues, and animal manure. This process occurs in the absence of oxygen, with microorganisms breaking down organic matter and producing a gas mixture, primarily composed of methane (CH_4) and carbon dioxide (CO_2) (Mirmohamadsadeghi et al., 2019). Biogas has gained attention as an environmentally friendly alternative to traditional fossil fuels due to its ability to generate heat, electricity, and serve as a vehicle fuel. The production process involves collecting various organic materials, which then undergo anaerobic digestion in controlled environments like biogas digesters. The resulting biogas composition varies based on the feedstock and the digestion process, typically consisting of 50-70% methane, with the remainder being primarily carbon dioxide (Chew et al., 2021). After production, biogas may undergo storage or treatment to remove impurities, enhancing its energy value. Biogas finds application in diverse ways. It can be directly burned for heating, used in combined heat and power systems for simultaneous electricity and heat generation, or upgraded to biomethane for injection into natural gas pipelines. Additionally, biogas can serve as a fuel for vehicles in compressed or liquefied forms. Advantages of biogas include its renewability, sustainable nature, and contribution to circular waste management practices. By capturing and utilizing methane, biogas systems help mitigate greenhouse gas emissions and offer an alternative to conventional fossil fuels, contributing to energy source diversification. Moreover, biogas serves as an effective solution for organic waste treatment, reducing pollution and the generation of harmful by-products. Challenges and considerations in biogas production include the availability and composition of suitable feedstock, the need for infrastructure and initial investment, ongoing technological advancements to enhance efficiency, and the integration of biogas into existing energy markets. Adequate feedstock collection and preprocessing are crucial for optimal performance, and policies supporting renewable energy incentives can facilitate market integration (Ferdeș et al., 2022). The future outlook for biogas is optimistic, given its potential environmental and economic benefits. As technology continues to advance, biogas is likely to play a vital role in the global transition to a more sustainable and resilient energy landscape. For food waste specifically, a full-scale digester receiving source-segregated domestic FW and monitored over 426 days produced 642 m3 biogas per tonne of VS added at a methane content of around 62%, with a potential recoverable energy of 405 kWh per tonne of input (Banks et al., 2011). The same plant illustrates the main limitation of FW mono-digestion: FW nitrogen (8.9 kg per tonne) led to high ammonia concentrations that may have caused the observed accumulation of volatile fatty acids (Banks et al., 2011). In

laboratory digesters, methane production stopped at a total ammonia nitrogen concentration of 2.3 g/L (Wang et al., 2025), and lipid ratios above 5% (wet weight) in an anaerobic membrane bioreactor increased the membrane fouling rate tenfold (Yan et al., 2026). Anaerobic digestion is the only food-waste conversion route in this review supported by long-term full-scale operating data; in a small-scale economic case study, biogas from mixed FW broke even at US$0.2944/m3 (Al-Wahaibi et al., 2020).

Bioethanol

Bioethanol is a renewable fuel produced through the fermentation of sugars or starches found in plants. Derived from crops like corn or sugarcane, it serves as an alternative to traditional gasoline. The production process involves cultivating and harvesting the feedstock, preprocessing it through milling or grinding, and then subjecting it to fermentation. During this biological process, microorganisms convert sugars into ethanol and carbon dioxide. Subsequent distillation separates ethanol from the fermentation mixture, followed by optional dehydration to remove remaining water, enhancing its purity. The final product is often blended with gasoline, creating ethanol fuel blends such as E10 or E85 for use in conventional gasoline engines (Singh et al., 2022). Advantages of bioethanol include its renewable nature, reduced greenhouse gas emissions compared to gasoline, contribution to energy security, compatibility with existing infrastructure, and its potential to support the agricultural sector. The cultivation of crops for bioethanol production offers economic benefits to farmers and helps diversify fuel sources. Challenges and considerations include concerns about land use and competition with food production, the energy balance of bioethanol, potential resource intensity, and ongoing research focused on technological advancements. The latter aims to improve production efficiency, explore advanced feedstocks, and optimize fermentation and distillation processes. Bioethanol remains a key player in the pursuit of sustainable and renewable fuel sources (Singh et al., 2022). Ongoing advancements in technology and research are addressing challenges and enhancing its viability as a clean energy alternative, contributing to a more sustainable energy landscape. Bioethanol from food waste, rather than from energy crops, avoids competition with food production but yields dilute broths. Hydrothermal pretreatment (100-160 °C) and enzymatic hydrolysis of the organic fraction of municipal solid waste yielded 191.10 g ethanol/kg dry matter with the inhibitor-tolerant fungus *Mucor indicus*, and digestion of the stillage added 156 L CH4/kg (Mahmoodi et al., 2018). Pineapple waste reached 85% of the theoretical ethanol yield, corresponding to only 3.9% ethanol (Salafia et al., 2022). For acetone-butanol-ethanol (ABE) fermentation, 81 g/L FW produced 18.9 g/L ABE with *Clostridium beijerinckii*, but higher FW loadings were limited by butanol inhibition unless butanol was removed in situ by vacuum stripping (Huang et al., 2015). These results are laboratory-scale; a techno-economic model of a 10 t/day FW-to-ethanol plant identified the ethanol price and the FW treatment fee as the most important economic variables (Chen et al., 2022).

Biodiesel

Biodiesel stands as a renewable and biodegradable fuel, sourced primarily from organic materials like vegetable oils, animal fats, and used cooking oils. It serves as an eco-friendly alternative to conventional diesel fuel, undergoing a process called transesterification for production. In this process, triglycerides within the feedstocks react with alcohol and a catalyst, resulting in the conversion of triglycerides into biodiesel and glycerol. Feedstock collection involves obtaining substances like soybean oil, canola oil, palm oil, animal fats, and used cooking oil. The transesterification process breaks down these feedstocks into biodiesel and glycerol, with subsequent steps involved in purification and separation. Biodiesel offers several advantages (Pour & Makkawi, 2021). Being renewable and biodegradable, it provides an environmentally friendly option. It also tends to have lower greenhouse gas emissions compared to traditional diesel, contributing to reduced environmental impact. Its compatibility with existing infrastructure allows it to be used in conventional diesel engines without modifications. Additionally, biodiesel contributes to diversifying fuel sources, potentially enhancing energy security. The use of waste products, such as used cooking oil and animal fats, in biodiesel production adds further value. However, challenges and considerations exist. The availability of suitable feedstocks and concerns regarding land use, especially when specific crops are grown for biodiesel, must be carefully managed to avoid negative environmental impacts. The energy intensity of biodiesel production is subject to debate, considering various inputs like cultivation, processing, and transportation. Cold weather performance may be a concern, as biodiesel has a higher cloud point and can gel at lower temperatures compared to traditional diesel. Compatibility issues with certain engines, especially older ones, may necessitate modifications or pose challenges with specific blends. Ongoing research focuses on addressing these challenges, improving production efficiency, and exploring new feedstocks to enhance the viability of biodiesel as a sustainable alternative to traditional diesel fuel (Patel et al., 2019). Food-waste-specific evidence comes from laboratory studies: a two-step conversion of lipidic FW recovered 92.6% fatty acid methyl esters (FAME) on a lipid basis (Almutairi et al., 2021), and an integrated scheme combining extraction of FW oil with heterotrophic microalgae grown on the FW hydrolysate produced 248.21 g FAME per kg FW (Patel et al., 2019).

Biohydrogen

Biohydrogen stands as a clean and renewable energy source produced through biological processes, particularly by certain microorganisms during fermentation. Unlike conventional hydrogen production methods that often involve fossil fuels, biohydrogen offers an environmentally friendly alternative. Microorganisms, including bacteria, cyanobacteria, and algae, play a crucial role in biohydrogen production through various biochemical pathways. In dark fermentation, certain anaerobic bacteria break down organic compounds in the absence of light, producing hydrogen as a byproduct. Photofermentation involves photosynthetic bacteria, like purple non-sulfur bacteria, which use light energy to produce hydrogen from organic compounds (Habashy et al., 2021). Direct biophotolysis utilizes microorganisms like microalgae or cyanobacteria to directly convert light energy into hydrogen by splitting water molecules through photolysis. Biohydrogen brings several advantages. It is derived from renewable resources, making it a sustainable energy carrier. The use of organic waste or biomass as feedstock contributes to waste treatment and reduces greenhouse gas emissions. The biological diversity of microorganisms allows flexibility in feedstock selection and production methods, adapting to different environmental conditions. Additionally, certain microbial processes can yield a relatively high amount of hydrogen, potentially making biohydrogen production efficient. However, challenges persist. Improving the yield and efficiency of biohydrogen production is an ongoing challenge, requiring enhancements to microbial strains and process optimization. Ensuring the availability and sustainability of suitable feedstocks, such as organic waste or biomass, is crucial to avoid competition with food production. Developing cost-effective and scalable technologies remains a challenge, necessitating continuous optimization and innovation (Sampath et al., 2020). Maintaining stability in microbial processes, particularly in response to variations in feedstock and environmental conditions, is crucial for consistent yields. Efficient storage and distribution of hydrogen pose challenges that require advancements in technology and infrastructure. In continuous laboratory operation on food waste, an organic loading rate of 40 g VS/L·d gave a peak hydrogen production rate of 1.26 L/L·d, but sustained high loading lowered the pH to 4.71 and led to propionate and valerate accumulation; intermittent feed disturbance restored production and gave 64.1 mL H2/g VS added (Hu et al., 2026). Process stability under continuous feeding, rather than peak rate, therefore remains the main barrier to scale-up.

Biochar

Biochar is a form of charcoal created through the pyrolysis of organic materials like agricultural residues and wood waste. This process occurs in a low-oxygen or oxygen-free environment, resulting in a stable carbon-rich material with a porous structure. Biochar has gained attention for its diverse applications in agriculture, carbon sequestration, and environmental remediation. Produced through pyrolysis, biochar is characterized by its carbon-rich composition, porous structure, and stability. Its primary applications include soil amendment to improve structure and nutrient availability, carbon sequestration in soils, water filtration, livestock bedding, and as a source of renewable energy through the production of syngas and bio-oil (Elkhalifa et al., 2019). Biochar benefits soil by enhancing fertility, improving water retention, and supporting microbial activity. Its incorporation into soils sequesters carbon, contributing to climate change mitigation. Additionally, biochar finds use in water filtration, livestock management, and renewable energy production, providing a multifaceted approach to sustainable resource utilization. Advantages of biochar include its role in soil improvement, carbon sequestration, waste utilization, water quality improvement, and the potential to reduce greenhouse gas emissions. Its use in agriculture can enhance soil fertility, reduce reliance on synthetic fertilizers, and contribute to a circular economy by utilizing agricultural residues and biomass. However, challenges exist, such as the selection of suitable feedstocks, determining optimal application rates in agriculture, understanding the long-term effects on soil health, and addressing the economic viability of large-scale production. Ongoing research is crucial to unlock the full potential of biochar and address practical challenges in various applications (Johnravindar et al., 2021). Because food waste is wet, hydrothermal carbonisation (HTC), which operates on wet feedstock, has been argued to be more suitable for FW than pyrolysis or incineration (Saqib et al., 2019). For market food waste in Kampala, an integrated HTC-anaerobic digestion scenario diverted 91% of input waste from landfill and reached an energy efficiency of 69%, compared with 75% and 45% for anaerobic digestion alone (Somorin et al., 2023). Biochar produced from FW digestate by HTC followed by high-temperature post-carbonisation had an 88% stable carbon fraction, and its economics were most sensitive to the gate fee charged for digestate (Gamaralalage et al., 2025). These results are model-based, and pilot-scale data for FW biochar were not found in the reviewed literature.

Solid fuel - pellets and briquettes

Solid fuels, in the form of pellets and briquettes, offer efficient and sustainable alternatives to traditional fuels like wood or coal. Pellets are small cylindrical pieces made from compressed biomass, often wood or agricultural residues. Briquettes, on the other hand, are larger, block-shaped solid fuels produced through the compression of finely divided biomass, usually with the addition of a binder. The advantages of pellets and briquettes lie in their higher energy density

compared to raw biomass, uniform shapes and sizes, ease of handling, and their renewable and sustainable nature. Their compact forms allow for efficient storage and transportation, and their standardized shapes contribute to consistent combustion characteristics (Espinoza-Tellez et al., 2020). Both pellets and briquettes are widely used in residential heating, industrial processes, and power generation. These solid fuels contribute to environmental sustainability by reducing reliance on non-renewable fossil fuels. Combustion of pellets and briquettes tends to produce fewer emissions compared to traditional fuels, thus improving air quality and contributing to reduced greenhouse gas emissions. Their versatility allows them to be used in various heating appliances, providing flexibility to meet diverse energy needs. However, challenges exist, including the need for a sustainable and available biomass feedstock, ensuring consistent quality standards, developing infrastructure for production and distribution, considering cost implications, and ongoing innovation to improve production efficiency and combustion characteristics. Pellets and briquettes play a significant role in the transition to cleaner and more renewable energy sources (Nikiema et al., 2022). As technology advances and awareness grows, their adoption is expected to expand across different sectors, contributing to a more sustainable and low-carbon energy future. For restaurant food waste, briquettes made from decomposed FW had an 18% higher net calorific value and a 24% lower burning rate than briquettes made from fresh FW (Nikiema et al., 2022).

Bio-oil

Bio-oil derived from food waste represents a sustainable and environmentally friendly alternative in the realm of renewable energy. Through the process of pyrolysis, food waste undergoes thermal decomposition in the absence of oxygen, producing a liquid substance known as bio-oil. This bio-oil is a complex mixture containing various oxygenated hydrocarbons and phenolic compounds, making it a versatile resource for multiple applications. For example, consider the conversion of food waste, such as fruit and vegetable residues, into bio-oil. In a pyrolysis reactor, the waste is subjected to high temperatures, typically between 400 and 600 degrees Celsius, initiating the breakdown of organic matter. The resulting bio-oil is rich in organic compounds, providing a valuable resource that can be harnessed for different purposes. Bio-oil from food waste holds significant potential for bioenergy production (Nayak & Bhushan, 2019). It can serve as a feedstock for the production of liquid biofuels, contributing to the reduction of dependence on traditional fossil fuels. The versatility of bio-oil extends to heat and power generation, where it can be utilized directly, although addressing its high-water content becomes essential in this context. Moreover, bio-oil extracted from food waste can find applications as a chemical feedstock. With suitable upgrading processes, it can be refined to yield bio-based chemicals, materials, or even pharmaceuticals. This utilization of food waste not only offers an eco-friendly alternative but also contributes to a circular economy by turning waste into a valuable resource. An additional benefit arises from the by-product of the pyrolysis process: biochar. This carbon-rich material can be employed as a soil amendment, enhancing soil fertility and promoting carbon sequestration. The integration of food waste into the bio-oil production process thus addresses environmental concerns and supports sustainable waste management practices. Despite its promise, challenges exist in optimizing the stability of bio-oil, addressing its high-water content, and ensuring economic viability (Mirmohamadsadeghi et al., 2019). Ongoing research and technological advancements aim to overcome these challenges, unlocking the full potential of bio-oil from food waste and contributing to a more sustainable and diversified energy and waste management landscape. A simulation of pyrolysis of cucumber, tomato and carrot wastes showed that bio-oil yield increased and biochar yield decreased with increasing temperature and feedstock moisture, while total energy demand also increased with moisture (Alherbawi et al., 2024). Separating mixed FW containing impurities into a slurry for anaerobic digestion and a solid fraction for pyrolysis reduced the nitrogen compounds in bio-oil by 62% compared with pyrolysis of whole FW (Okopi et al., 2024).

Biochemicals

The organic waste, comprising fruit and vegetable peels, trimmings, and by-products, undergoes a series of processes aimed at extracting valuable biochemicals. One prominent avenue is microbial fermentation, a bioconversion process that yields essential chemicals such as lactic acid and acetic acid. Lactic acid, integral in the production of biodegradable plastics, is derived from the breakdown of sugars within the organic waste by lactic acid bacteria. Simultaneously, acetic acid, with diverse industrial applications, can be produced through the fermentation of ethanol obtained from the waste (Kannah et al., 2020). Enzyme extraction is another facet of the valorization strategy. Certain food wastes, rich in enzymes, become a source for extracting amylases, proteases, and lipases. These enzymes, with their varied industrial applications spanning food, detergent, and pharmaceutical industries, contribute to the plant's commitment to resource efficiency. A pivotal element in this food waste valorization system is the biorefinery, where diverse biochemicals are extracted. This includes organic acids, bio-based solvents, and platform chemicals like succinic acid or 2, 3-butanediol. These chemicals, versatile in their applications, find use in the production of plastics, polymers, and various bio-based materials (Thygesen et al., 2021). The fermentation-based valorization of food processing residues has emerged as an efficient strategy for recovering high-value biomolecules. Munekata et al. (2021) highlighted the potential of fruit pomace generated during food processing as an inexpensive substrate for producing commercially

valuable compounds through microbial fermentation. Their review focused primarily on grape, apple, and olive pomace, demonstrating their suitability for the synthesis of carotenoids, fatty acids, linolenic acid, polyphenols, enzymes, and organic acids. These fermentation-derived products possess broad applications in food processing, including the development of functional foods. Despite the considerable industrial prospects, the authors emphasized the necessity for further research to establish efficient strategies for incorporating these fermentation-derived bioactive compounds into commercial food formulations (Munekata et al., 2021). Cheese whey represents another important agro-industrial by-product with significant potential for biotechnological conversion. Lappa et al. (2021) demonstrated that Generally Recognized as Safe (GRAS) microorganisms can effectively secrete extracellular enzymes exhibiting high catalytic efficiency, thereby enabling sustainable whey valorization within a circular bioeconomy framework. Their investigation employed a two-stage process involving fungal solid-state fermentation with *Aspergillus awamori* to generate crude enzymatic consortia. An integrated biorefinery concept for buffalo milk whey was proposed by Alfano et al. (2021), The permeate fraction was investigated as a source for producing reusable process water with reduced organic content, whereas the retentate was evaluated for multiple biotechnological applications. In addition, bioactive molecules isolated from the retentate promoted tissue regeneration during mammalian cell wound-healing assays, indicating promising applications in biomedical and cosmetic formulations. Microbial pigment production has gained increasing attention as a sustainable alternative to synthetic colorants used in the food industry. Mehri et al. (2021) investigated cheese whey as an economical and environmentally sustainable substrate for producing the natural red pigment synthesized by *Monascus purpureus*. Different whey preparations, including raw, demineralized, and deproteinized whey, were evaluated using a simultaneous hydrolysis and fermentation strategy. Food waste-derived microbial metabolites have also found applications in food formulation. Durval et al. (2021) evaluated a biosurfactant synthesized by *Bacillus cereus* cultivated on waste frying oil for its incorporation into cookie formulations. The application of fermentation-derived products has extended beyond the food sector into cosmetic and pharmaceutical industries. Ferracane et al. (2021) developed soaps using non-edible fermented olive oil (NEFOO) and evaluated their physicochemical characteristics during different ripening stages. Lactic acid and polyhydroxyalkanoates (PHA) are among the platform products most often targeted from food waste. Non-sterile fermentation of FW produced 69 g/L lactic acid at 86% yield in continuous mode (Peinemann et al., 2019), and for municipal biowaste, separate treatment of the food-derived and lignocellulosic fractions with continuous fermentation reached productivities of up to 12 g/L·h (Thygesen et al., 2021). A pilot plant operated for six months on food waste with mixed microbial cultures achieved a PHA content of 47.91% of dry cell weight at 9.94 g/L·d (Wu et al., 2023).

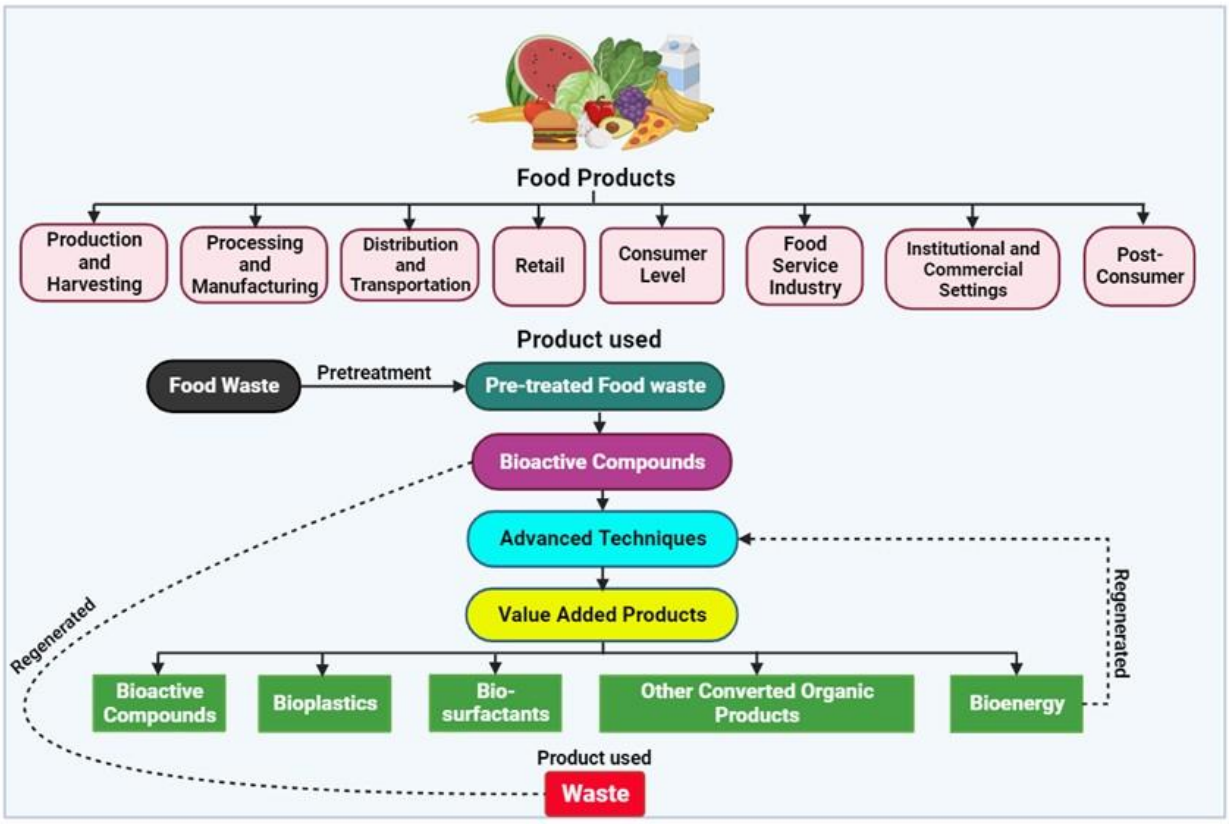


Figure. 3 Transforming Food Waste into Valuable Resources through Recovery and Upcycling.

Other value-added products

Food waste valorization extends its impact beyond the production of biochemicals, giving rise to an array of value-added products that contribute to sustainability and the circular economy. One avenue of valorization involves the extraction and processing of bioactive compounds present in food waste. Fruit and vegetable peels, often discarded, are rich in antioxidants and dietary fibers. These compounds can be harnessed to create dietary supplements, offering health benefits and transforming waste into a valuable resource. Aromatic compounds found in food waste contribute to its distinct flavors and smells. The extraction and isolation of these compounds open up opportunities for the production of natural flavors and fragrances. Industries such as food, cosmetics, and perfumery can benefit from these natural and sustainable alternatives. The pigments inherent in certain food waste, such as beetroot peels or grape skins, serve as natural colorants. Extracting and utilizing these pigments offer a sustainable option for the food and beverage industry, providing an eco-friendly alternative to synthetic dyes. Food waste, particularly those rich in starch or cellulose, can be harnessed for biopolymer production. These biopolymers become sustainable alternatives to conventional plastics, contributing to the reduction of plastic waste and promoting a more circular approach to materials. After extracting biochemicals or other compounds, the solid residues can be processed into nutrient-rich soil amendments. These amendments enhance soil fertility, promoting sustainable agriculture practices and completing the cycle of resource utilization (Lam et al., 2018). Specific biochemicals extracted from food waste can be further processed into specialty chemicals with diverse applications. For example, succinic acid or citric acid obtained from waste fermentation can find use in various industrial processes. Compounds with skincare benefits, including vitamins and polyphenols from certain food waste, can be isolated and incorporated into cosmetic products. These cosmeceuticals offer natural and sustainable alternatives in the cosmetic industry. Feedstock and food waste, primarily derived from agricultural sources, can be utilized for the production of single cell protein (SCP), serving as suitable protein supplements for both food and feed applications (Salafia et al., 2022). The technology involving microorganisms in single cell protein production offers a global solution to protein shortages, presenting a significant advantage due to its independence from climate, soil characteristics, and available land (Filho et al., 2018). In response to growing concerns about the ethical and environmental aspects of meat consumption, the use of filamentous fungi as a commercial food product has gained substantial attention. This is attributed to their high protein content, presence of essential amino acids, and easy digestibility (Esteban & Ladero, 2018). The conversion of food waste into protein-rich products through solid-state fermentation (SSF) has emerged as an effective strategy for promoting sustainable food systems and circular bioeconomy practices. Brancoli et al. (2021) investigated the application of SSF using the edible filamentous fungus *Neurospora intermedia* to transform surplus bread waste into a protein-enriched food ingredient. The authors proposed that this technology could be implemented either as an independent industrial process or directly within small-scale bakeries to recycle unsold bread into value-added products. Fermentation-based bioconversion has also been successfully applied to convert food processing residues into nutritionally valuable animal feed. Tropea et al. (2022) used a mixed substrate of fish, pineapple, banana, apple and citrus peels for single cell protein production by *Saccharomyces cerevisiae*, reaching up to 40.19% protein for use as animal feed. Fruit and olive pomaces generated during juice and olive oil production also represent valuable resources for livestock nutrition. In a comprehensive review, Munekata et al. (2021) examined the potential application of fermented pomaces as dietary supplements for animal production systems. Panyawoot et al. (2022) explored the effects of feed obtained through fermentation on final consumers. Their study evaluated the impact of fermented discarded durian peel, a seasonal tropical fruit, with *Lactobacillus casei*, cellulase, and molasses individually or in combination in total mixed rations. Insect bioconversion has been demonstrated at pilot scale: a continuous black soldier fly reactor operated for nine weeks achieved 55.1% material degradation and 11.8% biomass conversion on a total-solids basis, and reduced *Salmonella* spp. and viruses (Lalander et al., 2015). Regulatory acceptance is a binding constraint for feed and protein routes; direct feeding of heat-treated FW to pigs is currently illegal for most FW in the European Union because of disease-control concerns (Salemdeeb et al., 2017), and industrial protein extraction from FW remains underutilised and generally suited to low-quality products (Kamal et al., 2021).

Comparative synthesis of conversion routes

Table 2 compares the conversion routes discussed above using the same criteria. Among them, only anaerobic digestion is supported by long-term full-scale operating data (Banks et al., 2011); mixed-culture PHA and black soldier fly bioconversion have pilot-scale evidence (Wu et al., 2023; Lalander et al., 2015), and the remaining routes are documented at laboratory scale or by process simulation. The principal limitations differ by route: ammonia and lipid inhibition for anaerobic digestion (Wang et al., 2025; Yan et al., 2026), low pH and acid accumulation for dark fermentation (Hu et al., 2026), product inhibition for ABE fermentation (Huang et al., 2015), and feedstock moisture for pyrolysis (Alherbawi et al., 2024).

Novel separation processes for bioproducts

In recent times, several research endeavors have focused on advancing innovative and efficient separation processes and methodologies. These methods operate based on selective criteria to recover bioproducts from complex reaction media and under specific purification conditions. Conventional technologies face challenges such as high thermal sensitivity caused by biomass, low volatility, and high reactivity (Chen et al., 2018). Additionally, these traditional methods tend to be more expensive and energy-intensive, particularly in processes involving bioproduct separation from dilute solutions. To address these challenges, novel separation technologies have emerged, including solvent extraction in biphasic systems (Cai et al., 2016), reactive adsorption using zeolite, chromatography, membrane technology, and carbon sorbents. These technologies have been developed for diverse applications, showcasing their effectiveness in bioproduct separation. Concurrently, various alternative separation options have been explored. Multi-scale simulations have played a crucial role in predicting solvent selection and optimizing adsorption separation. Numerous novel separation techniques have demonstrated high potential for the future of biorefineries. It is imperative to optimize factors influencing separation performance and strategically minimize existing gaps. Exploring additional opportunities for future development is also a viable avenue (Cai et al., 2017). A variety of applications for separation technologies have been documented in the realm of applied biology, where efforts have been directed towards conceptualizing approaches within the field and subsequently refining their focus for processing fermentative products. These products often manifest as valuable biological substances, including nucleotides and proteins. Comprehensive discussions have taken place regarding the significance and general characteristics of these products. Within this framework, extensive exploration of large fields, major trends, and strategic approaches has yielded highly fruitful outcomes in the realm of effective separation and purification processes (Nguyen et al., 2017). Detailed insights into individual separation equipment and the principles governing their separation performance are provided. Researchers have delved into existing literature to offer insights to the reader, providing a foundation for setting representative basic references and instilling hope. Numerous promising new developments and specialized reviews on bio-separation processes and technologies have been uncovered in various literature sources (Moharkar & Dhamole, 2021). **Figure.4** illustrates the application of these novel separation technologies for metabolites. In this revised review, separation evidence is classified as "demonstrated" when the cited study used food waste, a food-processing by-product or a food-processing effluent, and as "transferable" when it used model solutions or non-food feeds; examples without a demonstrated or justified food-waste application have been removed (Table 3).

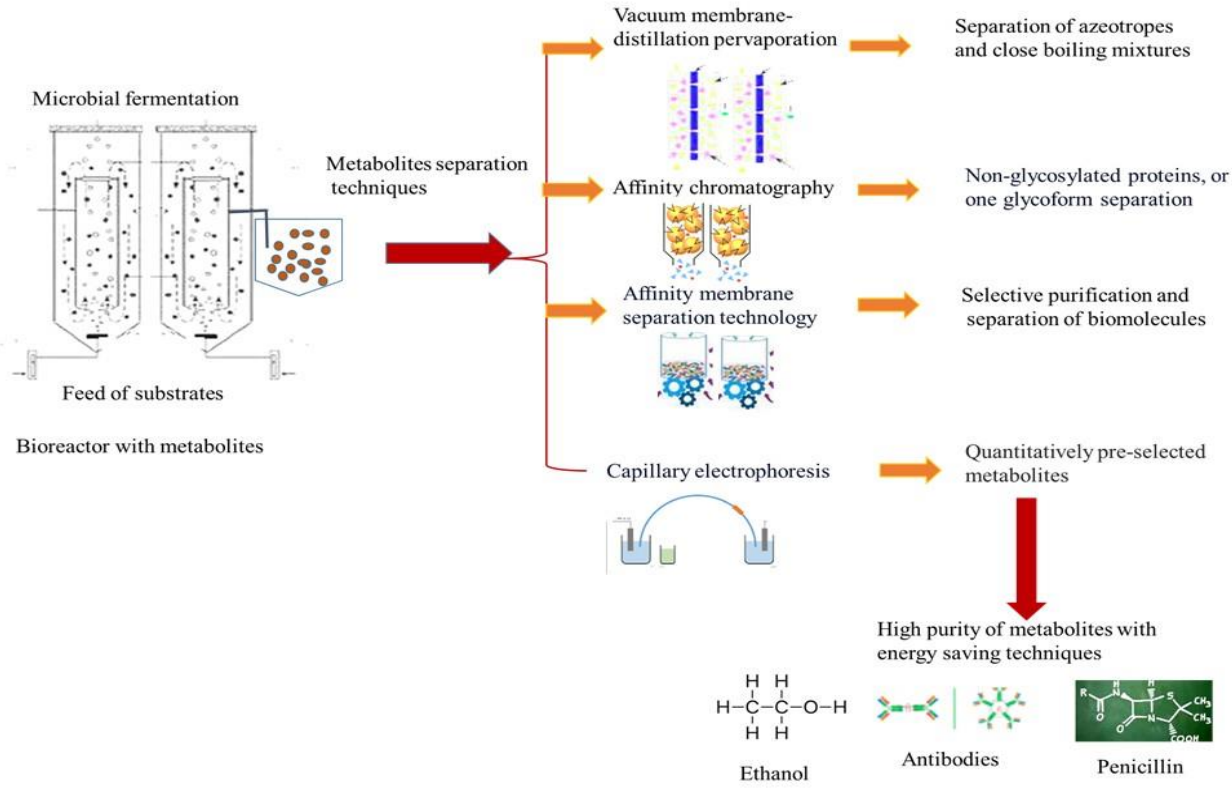


Figure. 4. Applications of novel separation technologies for metabolite production (generic schematic of separation principles; the products shown illustrate the original application domains of these techniques and are not food-waste products; food-waste-specific evidence is given in Table 3).

In the sphere of bioproduct separation, hybrid in situ separation systems, in conjunction with conventional distillation, have been recognized as effective methods. The conventional distillation process, known for its efficacy, employs a high reflux ratio in the ethanol column. However, challenges arise from the accumulation of ethanol on the tops of the water and butanol column, leading to poor controllability and increased operational costs (Chen et al., 2018). A vacuum distillation process, specifically based on a decanter-assisted ethanol-butanol recycle loop (E-TCD) sequence, has been developed to enhance the conventional separation sequence for ABE (acetone, butanol, and ethanol) separation. The feed for this process utilizes the permeate from an in-situ pervaporation system, with subsequent simulation and optimization conducted through iterative strategies (Chen et al., 2018). An ABE mixture, boasting elevated concentrations of acetone (115.8 g/L), butanol (191.4 g/L), and ethanol (17.8 g/L), was achieved through a fermentation-pervaporation integration process. This mixture, in turn, served as the feed for a scaled plant producing 1025 kg/h of ABE mixture with high product purities-100 wt% butanol, 99.7% acetone, and 95% ethanol (Chen et al., 2018). Notably, the energy cost for butanol during the ABE separation process is reported at 5.3 MJ/kg, constituting only 37.54% of the total energy cost incurred in conventional distillation processes. These values were obtained by process simulation with a feed that was not derived from food waste, and are therefore cited as a transferable benchmark rather than as demonstrated food-waste performance (Chen et al., 2018). Table 3 summarises separation evidence for food-waste-derived products, distinguishing demonstrated from transferable applications. For each separation method, three questions determine its value in a food-waste biorefinery: what problem it solves, how it compares with the conventional alternative, and what the improvement costs. Pressure-driven membranes fractionate dilute by-products without thermal damage. In whey processing, ultrafiltration concentrates protein and nanofiltration concentrates lactose; diafiltration purifies both but consumes three times the initial whey volume of water, of which 66% was reclaimed as drinking water by reverse osmosis and activated carbon, while a protein concentrate with 88% protein and lactose of 90% purity were produced (Brião et al., 2024). Buffalo whey has been ultrafiltered in-house at a dairy factory, with nanofiltration used to recover water for reuse (Alfano et al., 2021). For orange press liquor, ultrafiltration followed by nanofiltration and osmotic distillation concentrated flavonoids from 10 to 47 g total soluble solids per 100 g at laboratory scale (Cassano et al., 2014). The cost of these improvements lies in water demand and fouling; a quantitative energy comparison with thermal evaporation for these streams was not reported in the reviewed sources. In situ product recovery addresses product toxicity in solvent fermentation. Vacuum stripping integrated with ABE fermentation of food waste kept ABE below 10 g/L and allowed fermentation at 129 g/L FW with a productivity of 0.49 g/L·h (Huang et al., 2015). Among extraction-based ABE recovery systems (non-FW feed, simulation), energy requirements of 6.4-8.3 MJ-fuel/kg ABE were reported for hybrid processes, with the in-situ recovery, direct steam distillation and mixture extraction options having the lowest energy demand and total annualised cost (Díaz & Tost, 2017). Pervaporation membranes of polydimethylsiloxane loaded with ZIF-8 nanoparticles increased flux by 350% relative to neat polydimethylsiloxane in aqueous model solutions (Zamani et al., 2023); their performance in food-waste broths containing salts, lipids and proteins has not been reported. For organic acids, conventional lactic acid recovery by precipitation generates gypsum as a by-product; selective adsorption on hyper-crosslinked polymers enabled gypsum-free lactic acid recovery from aqueous model solutions (Rübenach et al., 2019), and for biowaste-derived lactic acid, reactive distillation and emulsion liquid membranes achieved purities sufficient for polylactic acid production (Thygesen et al., 2021). Supercritical CO2 extraction offers a solvent-free alternative to hexane for lipophilic bioactives: from tomato pomace, 84.6% of the lycopene was extracted but only 48.4% of the extracted lycopene was recovered in the extract because recovery was limited by its solubility in the co-extracted tomato oil (Squillace et al., 2020). For mixed food waste, simple pre-separation into a slurry and a solid fraction raised the methane potential of the digested fraction from 294.37 to 572.88 mL/g VS and gave the most favourable energy balance and economics among the configurations compared (Okopi et al., 2024).

Techno-economic analysis

Techno-economic assessment (TEA) of food-waste biorefineries is constrained by low technology readiness, which has led to screening-level estimates of investment, manufacturing cost, return on investment and payback (Cristóbal et al., 2018). Table 4 compiles TEA indicators reported specifically for food-waste systems; values are not directly comparable because scale, currency, base year, discount rate and system boundary differ among studies. Product price dominates profitability. For a 1 t/day plant co-producing a plasticiser and lactic acid, the lactic acid price was the largest determinant of profit (net present value US$3,028,000; payback 7.56 years; internal rate of return 18.98%), whereas the variant producing plasticiser and animal feed ran an annual deficit of US$42,632 (Kwan et al., 2015). For a fish- and mollusc-residue biorefinery, profitability depended mainly on the selling price of protein hydrolysates, which also accounted for 72.5-83.8% of operating costs, and the payback period was 2.9 years (Andreola et al., 2023). Gate fees and treatment fees can be decisive: for fuel ethanol from FW at 10 t/day, capital cost was US$367,552 and the shortest payback was 5 years at a 5% discount rate, with ethanol price and FW treatment fee as the most sensitive variables (Chen et al., 2022). Scale thresholds also exist, since non-sterile lactic acid production from FW became profitable only

for catchments of 200,000 or more inhabitants (Peinemann et al., 2019). Integrated configurations performed better than single-product configurations where both were assessed. For enzymatic hydrolysis of the organic fraction of municipal solid waste, on-site enzyme production combined with solid-state fermentation gave an internal rate of return of 13% and a 6-year payback, whereas purchasing commercial enzymes made the biorefinery unprofitable (Molina-Peñate et al., 2024). Pre-separation of FW into a slurry for anaerobic digestion and solids for pyrolysis gave a net present value of US$15 million and an internal rate of return of 34% (Okopi et al., 2024), and sophorolipid production from FW was economically feasible in all four scenarios evaluated for Hong Kong (Wang et al., 2020). Most of these TEAs are model-based and use laboratory yields; minimum selling prices, sensitivity to feedstock compositional variability and the cost of contaminant removal are rarely reported, and verified food-waste TEA data for PHA and butanol were not found.

Environmental sustainability and life-cycle evidence

Life-cycle assessment (LCA) has been applied to food-waste valorization to value-added products (Lam et al., 2018), and its results depend on the products displaced, residue management and energy supply (Table 5). Among conventional treatment options in the United Kingdom, anaerobic digestion had the lowest impacts in 13 of 19 impact categories, including a net-negative global warming potential, whereas in-vessel composting was the least sustainable option (Slorach et al., 2019). Converting FW into pig feed scored best in most impact categories compared with anaerobic digestion and composting, largely because it displaces conventional feed (Salemdeeb et al., 2017). Black soldier fly treatment had direct greenhouse gas emissions 47 times lower than windrow composting, but post-composting of the residue contributed 69% of its global warming potential (Mertenat et al., 2019). For higher-value products the trade-offs are sharper. The pilot PHA plant described above had a fossil depletion potential 10.30 and 7.59 times that of petroleum-based polyethylene in two scenarios, and an environmental advantage was obtained only when the plant was integrated within a resource-energy-water union (Wu et al., 2023). For fungal protein from surplus bread, inoculum production and solid-state fermentation were the environmental hotspots (Brancoli et al., 2021), and biochar from FW digestate gave net reductions of 1.15-1.20 t CO_2-eq per tonne of biochar when co-located with anaerobic digestion to minimise digestate transport (Gamaralalage et al., 2025). Other reported trade-offs include water use in downstream processing, since diafiltration consumes three times the whey volume of water (Brião et al., 2024), and plastic contamination from food packaging, which affects digestate quality (Murcia et al., 2026). Comparative toxicity data for solvents and chemicals used in FW-derived product purification were not found in the reviewed literature.

Future prospectives

The future of food waste valorization for resource recovery is poised for significant advancements in technologies and separation processes. This evolving landscape promises a more efficient and sustainable approach to managing organic waste. Technological innovations will likely be a focal point of future research. Advances in extraction, fermentation, and conversion technologies are expected to enhance the overall efficiency of resource recovery processes. These innovations will contribute to the development of more precise and targeted approaches in valorizing food waste. Novel separation processes, such as membrane technologies, supercritical fluid extraction, and advanced chromatography, are anticipated to be integrated into food waste valorization. These techniques offer precise separation and purification of target compounds, leading to higher yields and improved purity in the extracted products (Ma and Liu, 2019). The future may witness a shift towards precision valorization, where specific waste streams are meticulously targeted for the recovery of valuable compounds. This approach requires a deeper understanding of the composition of different food waste streams, allowing for tailored processes that maximize resource recovery. Integration with the circular economy is expected to become more pronounced. Food waste valorization will likely be intricately linked with broader sustainability principles, creating closed-loop systems where waste from one process becomes a resource for another. The application of artificial intelligence (AI) and big data analytics is anticipated to optimize food waste valorization processes. These technologies can analyze extensive datasets related to waste composition, processing parameters, and market demands, leading to more informed decision-making and resource-efficient operations (Barba et al., 2019). Future advancements may enable the simultaneous extraction of multiple high-value products from food waste. Integrated biorefinery approaches could become more prevalent, allowing for the production of various biochemicals, biopolymers, and other valuable materials in a single valorization facility. Efficient waste-to-energy technologies are likely to play a crucial role in the future of food waste valorization. Advanced methods, such as plasma gasification or microbial fuel cells, may gain prominence for converting organic waste into energy, contributing to renewable energy sources. Diversification of markets for products derived from food waste is expected in the future. Industries such as pharmaceuticals, cosmetics, and specialty chemicals are likely to explore and adopt sustainable and bio-based alternatives, contributing to market expansion. Anticipated regulatory support and standardization efforts will encourage the adoption of food waste valorization technologies (Gómez-García et al., 2021). Clear guidelines and incentives may accelerate the integration of these processes into mainstream waste management practices. Increased public awareness

of the environmental impact of food waste and the potential of valorization is expected. Education campaigns and outreach initiatives will likely play a role in shaping public perception and encouraging responsible waste management practices (Tamasiga et al., 2022). In summary, the future of food waste valorization holds promise for a more efficient, sustainable, and environmentally conscious approach to managing organic waste. Technological advancements, precision valorization, circular economy integration, and increased public awareness are key factors shaping the trajectory of this evolving field. Building on these advances, an integrated biorefinery can route each food-waste stream through characterisation, pretreatment, primary product recovery, secondary product recovery, purification, energy recovery and residue utilisation, with the objective of minimising the final residue (Figure 5). This sequence follows the cascade principle for integrating bioprocesses (Dahiya et al., 2018) and the two-stage approach of direct valorization followed by conventional treatment of residual streams (Esparza et al., 2020). For dairy whey, protein and lactose can be recovered by membranes with diafiltration water reclaimed (Brião et al., 2024), followed by enzymatic lactose hydrolysis and bacterial cellulose production (Lappa et al., 2021); for fruit-processing residues, pectin, D-limonene and flavonoids can be co-extracted from orange peel (Pfaltzgraff et al., 2013) and lycopene from tomato pomace (Squillace et al., 2020) before the residual solids are fermented or digested; and for mixed FW, pre-separation (Okopi et al., 2024), enzymatic hydrolysis with on-site enzymes (Molina-Peñate et al., 2024), fermentation to lactic acid (Peinemann et al., 2019), digestion of residues and conversion of digestate to biochar (Gamaralalage et al., 2025) can be combined. The framework is conceptual, because no study in the reviewed literature has operated a complete cascade at pilot or full scale.

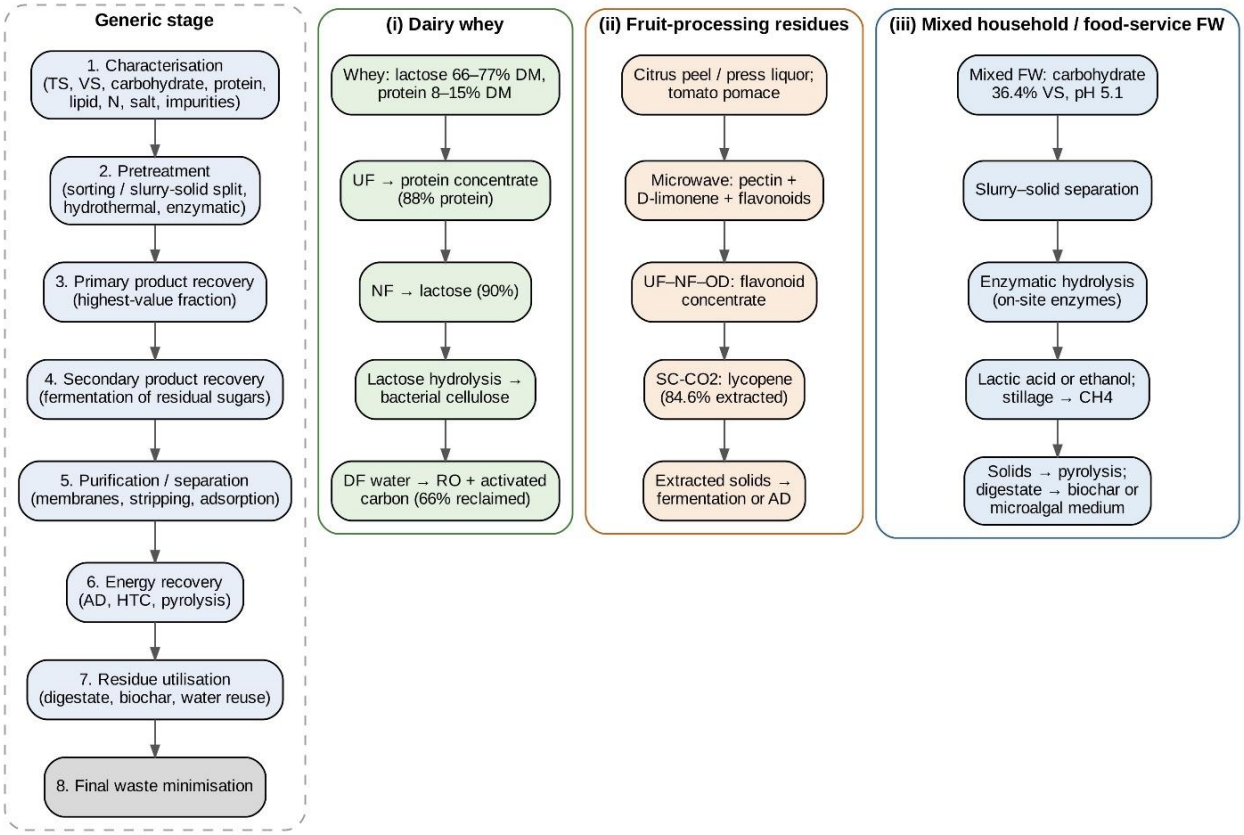


Figure 5. Integrated feedstock-to-residue framework for food-waste biorefineries (left) with three worked cascades.

Values shown are those reported in the cited studies: (i) dairy whey (Lappa et al., 2019; Brião et al., 2024; Lappa et al., 2021; Alfano et al., 2021); (ii) fruit-processing residues (Pfaltzgraff et al., 2013; Cassano et al., 2014; Squillace et al., 2020; Esparza et al., 2020); (iii) mixed household and food-service FW (Fisgativa et al., 2016; Okopi et al., 2024; Molina-Peñate et al., 2024; Peinemann et al., 2019; Mahmoodi et al., 2018; Gamaralalage et al., 2025; Parakh & Tong, 2025). Limitation: the framework is conceptual; mass and energy balances across complete cascades are not available. DF, diafiltration; DM, dry matter; NF, nanofiltration; OD, osmotic distillation; RO, reverse osmosis; SC-CO2, supercritical CO2; UF, ultrafiltration; VS, volatile solids. Several specific research gaps emerge from the evidence reviewed here. (1) Mixed-feedstock variability: 24% of the variation in FW characteristics is explained by origin, source and season (Fisgativa et al., 2016), yet TEAs rarely test sensitivity to composition. (2) Inhibitor formation during

pretreatment: hydrothermal pretreatment of FW at 180 °C produced about 8 mg/g dry solids of 5-hydroxymethylfurfural, which inhibited composting microorganisms (Nakasaki et al., 2015). (3) Ammonia and lipid inhibition in biological conversion (Wang et al., 2025; Yan et al., 2026). (4) Membrane fouling under realistic conditions, since available fouling studies include work on synthetic FW (Ariunbaatar et al., 2021). (5) Solvent recovery from dilute broths, for which the most energy-efficient sequences have been demonstrated only by simulation on non-FW feeds (Chen et al., 2018). (6) Downstream purification cost, which is rarely reported separately from conversion cost. (7) Contamination and safety of recovered products, including pathogens, plastics and feed-law restrictions (Salemdeeb et al., 2017; Murcia et al., 2026). (8) Scale-up, since most FW valorization pathways remain at laboratory scale (Caldeira et al., 2020). (9) TEA and LCA uncertainty, as uncertainty analysis is uncommon; one exception used Monte Carlo simulation (Zheng et al., 2025). (10) Product-market constraints and integration of multiple product streams, since profitability depends on product prices and economies of scale that increase feedstock logistics (Kwan et al., 2015; Cristóbal et al., 2018). The corresponding research priorities are composition-resolved datasets coupled to TEA sensitivity analysis, pretreatment windows that limit furan formation, stream-specific routing of protein- and lipid-rich FW, fouling studies on real FW broths, integrated fermentation-recovery trials with measured energy demand, TEAs that separate purification costs, contaminant-fate studies aligned with feed and fertiliser regulations, pilot campaigns that report mass, energy and environmental data together, harmonised TEA/LCA boundaries with uncertainty analysis, and market-volume analysis for FW-derived products).

Conclusions

The evolving landscape of food waste valorization for resource recovery holds tremendous promise in addressing the pressing challenges of waste management while fostering sustainability and resource efficiency. The integration of advanced technologies and novel separation processes is poised to revolutionize the way we perceive and manage food waste. The advancements in extraction, fermentation, and conversion technologies signify a paradigm shift towards more efficient and targeted resource recovery. The application of novel separation processes, including membrane technologies and supercritical fluid extraction, enhances the precision and purity of extracted compounds, unlocking new possibilities for valuable product streams. The future trajectory of food waste valorization points towards a more tailored and precise approach. Understanding the composition of diverse waste streams allows for customized processes, maximizing the recovery of high-value compounds and contributing to a more sustainable and circular economy. The integration of food waste valorization with the principles of the circular economy is a notable highlight. Creating closed-loop systems where waste becomes a resource for new processes aligns with broader sustainability goals and underscores the potential for holistic and environmentally conscious waste management. Technological advancements, coupled with the potential of artificial intelligence and big data analytics, pave the way for optimized and informed decision-making in resource recovery processes. The simultaneous extraction of multiple high-value products from food waste and the exploration of waste-to-energy technologies further showcases the versatility and comprehensive nature of valorization approaches. As markets diversify and regulatory support strengthens, the adoption of food waste valorization technologies is expected to accelerate. Clear guidelines and incentives create an environment conducive to the widespread integration of these innovative processes into mainstream waste management practices. The future of food waste valorization is not just a technological evolution; it is a societal shift towards increased awareness and responsible waste management. Education campaigns and outreach initiatives will play a pivotal role in shaping public perception and fostering a collective commitment to sustainable practices. The evidence reviewed supports more specific conclusions. Feedstock composition should determine routing, because mixed FW, whey, fish by-products and bread waste differ fundamentally in their carbohydrate, protein, lipid and mineral contents (Fisgativa et al., 2016; Lappa et al., 2019; Coppola et al., 2021; Narisetty et al., 2021). Anaerobic digestion is the only conversion route with long-term full-scale data in the reviewed literature (Banks et al., 2011), whereas fermentation, PHA, protein and thermochemical routes are documented at laboratory, pilot or simulation level. Separation remains the least-evidenced link, with the most efficient solvent-recovery results obtained by simulation on non-FW feeds (Chen et al., 2018). Food-waste TEAs show that profitability depends on product price, gate fees, enzyme supply and catchment scale (Kwan et al., 2015; Chen et al., 2022; Molina-Peñate et al., 2024; Peinemann et al., 2019), and life-cycle benefits are conditional on displaced products and system integration (Slorach et al., 2019; Wu et al., 2023). Pilot-scale integration of conversion, separation and residue management, reported with complete mass, energy, economic and environmental data, is therefore the most urgent research priority.

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Table 1. Major food-waste streams, reported composition, conversion constraints and routes with food-waste-specific evidence. Values are as reported in the cited source and on the basis stated; DM, dry matter; DW, dry weight; VS, volatile solids; COD, chemical oxygen demand; TAN, total ammonia nitrogen.

Food-waste stream	Reported composition (basis)	Key constraints for conversion	Routes with FW-specific evidence	Source
Mixed household and food-service FW	Carbohydrates 36.4% of VS; pH 5.1 (70-study compilation); extractable oil 14.15% w/w (one study)	Variability (24% explained by origin, collection source, season); acidification; high TAN and Na in Asian FW; physical impurities	Anaerobic digestion; ethanol; lactic acid; ABE; PHA; slurry-solid separation with pyrolysis	(Fisgativa et al., 2016; Patel et al., 2019; Okopi et al., 2024; Banks et al., 2011; Peinemann et al., 2019; Huang et al., 2015; Wu et al., 2023)
Fruit and vegetable residues (peels, pomace, press liquor)	Pineapple waste: soluble sugars 32.12%, insoluble sugars 26.33%	Perishable and heterogeneous; logistics	Extraction (pectin, flavonoids, lycopene); fermentation to ethanol and protein; pyrolysis	(Esparza et al., 2020; Salafia et al., 2022; Pfaltzgraff et al., 2013; Cassano et al., 2014; Squillace et al., 2020; Alherbawi et al., 2024)
Bakery and bread waste	Starch-rich, easily extractable fermentable sugars; quantitative composition: -	Short material lifetime and hygiene requirements limit direct food recycling	Fermentation to chemical building blocks; fungal protein by solid-state fermentation	(Narisetty et al., 2021; Brancoli et al., 2021)
Dairy whey	≈50% of milk solids; DM: lactose 66-77%, protein 8-15%, minerals 7-15%; COD 50,000-80,000 mg/L (compiled)	High organic load; strain specificity for lactose limits product range	UF/NF/DF to protein concentrate and lactose; enzymes and bacterial cellulose; pigments; probiotic substrate	(Lappa et al., 2019; Lappa et al., 2021; Brião et al., 2024; Mehri et al., 2021; Alfano et al., 2021)
Fish and seafood residues	DW: protein 49.22-57.92%, ash 21.79-30.16%, fat 7.16-19.10% (compiled)	Lipid oxidation and hydrolysis variability	Protein hydrolysates, calcium carbonate, co-composted biochar; protein-enriched feed	(Coppola et al., 2021; Andreola et al., 2023; Tropea et al., 2022)
Lipid-rich FW and waste cooking oil	FAME recovery 92.6% (lipid basis)	Long-chain fatty acid stress; membrane fouling in AnMBR above 5% lipid (wet weight)	Biodiesel; biosurfactant	(Almutairi et al., 2021; Yan et al., 2026; Durval et al., 2021)
Food-processing effluents	Proteins and lipids; free of heavy metals (qualitative); quantitative composition: -	Dilute; composition rarely analysed	Membranes, adsorption, aqueous two-phase systems, foam fractionation; microalgal cultivation	(Lee & Stuckey, 2022)

Table 2. Comparative synthesis of food-waste conversion routes. Only values measured or modelled for FW feedstocks are reported; economic and environmental indicators are detailed in Tables 4 and 5.

Route	Suitable FW streams	Reported yield or recovery (FW feed)	Energy and chemical requirement	Major technical limitation	Scale of evidence	Economic indicator	Environmental implication	Source
Anaerobic digestion	Mixed FW; moderate-lipid FW	642 m³ biogas/t VS added, ~62% CH4; 405 kWh recoverable per t input	Biogas upgrading; trace-element supplementation	Ammonia (CH4 production stopped at TAN 2.3 g/L in a control digester); acidification	Full scale (426 d)	Biogas break-even US$0.2944/m³; discounted payback 6 y	Lowest impacts in 13 of 19 categories (UK)	(Banks et al., 2011; Wang et al., 2025; Al-Wahaibi et al., 2020; Slorach et al., 2019)
Dark fermentation (H2, VFA)	Carbohydrate-rich FW	64.1 mL H2/g VS added; peak 1.26 L/L·d	pH control; feed management	Low pH (4.71) and propionate/valerate accumulation	Laboratory (continuous)	FW-VFA as denitrification carbon: IRR 8.5%	-	(Hu et al., 2026; Zheng et al., 2025)
Ethanol	Starch-rich FW; OFMSW; fruit residues	191.10 g ethanol/kg dry OFMSW (+156 L CH4/kg from stillage); 85% of theoretical (3.9% ethanol) from pineapple waste	Hydrothermal pretreatment 100-160 °C; enzymes; distillation of dilute broth	Low titres; enzyme cost	Laboratory; TEA model (10 t/d)	Capital US$367,552; payback 5 y	-	(Mahmoodi et al., 2018; Salafia et al., 2022; Chen et al., 2022)
ABE fermentation	Starch-rich FW	18.9 g/L ABE, 0.38 g/g; 0.49 g/L·h with vacuum stripping	In situ product recovery	Butanol inhibition at ≥129 g/L FW	Laboratory	-	-	(Huang et al., 2015)
Lactic acid	Starch/sugar-rich FW; municipal biowaste	69 g/L at 86% yield (continuous); productivity up to 12 g/L·h	Glucoamylase; reactive distillation or liquid membranes for purification	Contamination risk (non-sterile); purification	Laboratory; TEA model	Profitable with FW from ≥200,000 inhabitants; LA price is key	-	(Peinemann et al., 2019; Thygesen et al., 2021; Kwan et al., 2015)
PHA (mixed cultures)	Fermented FW	47.91% of DCW at 9.94 g/L·d; 41.39% at 20.02 g/L·d	Three-stage mixed-culture process; optional rapid proliferation stage	High environmental burden of an isolated plant	Pilot (6 months)	-	Fossil depletion 7.59-10.30 times that of polyethylene	(Wu et al., 2023)

Biodiesel (FAME)	Lipid-rich FW; waste oils	92.6% FAME (lipid basis); 248.21 g FAME/kg FW (integrated)	Methanol and catalyst for transesterification	Feedstock variability	Laboratory	-	-	(Almutairi et al., 2021; Patel et al., 2019)
Microbial protein	Bread; pea-processing by-product; mixed peels; digestate	25-29% protein (fungal); 0.26 g protein/g; up to 40.19% (yeast); up to 62% (microalgae)	Inoculum production; nutrient supplementation	Industrial FW protein underutilised and mostly low-quality	Laboratory	Microalgal cultivation cost -66% vs synthetic medium	Hotspots: inoculum production and SSF	(Brancoli et al., 2021; Filho et al., 2018; Tropea et al., 2022; Parakh & Tong, 2025; Kamal et al., 2021)
Black soldier fly larvae	Mixed organic waste	55.1% material degradation; 11.8% biomass conversion (TS basis)	Electricity; residue post-composting	Residue post-treatment dominates GWP	Pilot (9-week continuous reactor)	-	Direct GHG 47 times lower than windrow composting	(Lalander et al., 2015; Mertenat et al., 2019)
Pyrolysis	Dried vegetable waste; FW solids	Bio-oil increased and biochar decreased with temperature and moisture; bio-oil N compounds -62% (solids fraction)	Drying; 300-500 °C	Moisture penalty on energy demand	Simulation; laboratory	ROI 29%, payback 3.4 y (5% moisture, 300 °C)	Water footprint increased with temperature	(Alherbawi et al., 2024; Okopi et al., 2024)
HTC and digestate biochar	Wet FW; FW digestate	HTC-AD energy efficiency 69%; biochar 88% stable carbon	HTC plus post-carbonisation	Gate-fee dependence; digestate transport	Model (TEA/LCA)	Mitigation cost US$125/t CO_2-eq	Net -1.15 to -1.20 t CO_2-eq/t biochar	(Somorin et al., 2023; Gamaralalage et al., 2025)
Extraction of food-grade compounds	Citrus peel; tomato pomace; whey	Lycopene: 84.6% extracted, 48.4% recovered; whey protein concentrates 88% protein	SC-CO_2 at high pressure; DF water three times whey volume	Solubility-limited recovery; DF water demand	Laboratory; whey UF at dairy-factory scale	-	Water consumption in DF	(Squillace et al., 2020; Brião et al., 2024; Alfano et al., 2021; Pfaltzgraff et al., 2013)

Table 3. Separation and downstream processing for food-waste-derived products. "Demonstrated" denotes an FW, food-processing by-product or effluent feed; "Transferable" denotes model solutions or non-FW feeds evaluated for principles applicable to FW streams; "Conceptual" denotes a design not experimentally validated. TRL is not assigned because the cited studies do not report it; the reported scale is given instead.

Food waste / feedstock	Target product	Pretreatment	Separation technology	Recovery / yield	Purity	Energy / chemical requirement	Economic indicator	Scale	Major limitation	Evidence type	Reference
Cheese whey	Protein concentrate; lactose; water	-	UF + NF + DF; RO + activated carbon for DF water	66% of DF water reclaimed as drinking water	Protein concentrate 88% protein; lactose 90%	DF water = 3 × whey volume	-	-	Water demand; fouling	Demonstrated	(Brião et al., 2024)
Buffalo whey	Protein retentate; reusable water	-	UF (20 kDa spiral) + NF	-	Water reused for machine rinsing	-	Lower disposal costs (qualitative)	Dairy-factory UF	-	Demonstrated	(Alfano et al., 2021)
Orange press liquor	Flavonoids	UF clarification	NF + osmotic distillation	Flavanones and anthocyanins highly rejected by NF	TSS 10 to 32 to 47 g/100 g	-	-	Laboratory	-	Demonstrated	(Cassano et al., 2014)
Tomato pomace	Lycopene	-	Supercritical CO2	84.6% extracted; 48.4% of extracted recovered	-	High-pressure CO2; co-solvent oil in	-	Laboratory	Lycopene solubility in tomato oil	Demonstrated	(Squillace et al., 2020)

						redesign					
FW fermentation broth (129 g/L FW)	ABE	Enzymatic hydrolysis of FW	Vacuum stripping (in situ)	ABE kept below 10 g/L; 0.49 g/L·h	-	Vacuum	-	Laboratory	-	Demonstrated	(Huang et al., 2015)
ABE permeate from fermentation-pervaporation (non-FW)	Butanol, acetone, ethanol	Pervaporation	Decanter-assisted vacuum distillation (E-TCD)	1025 kg/h plant (simulated)	Butanol 100 wt%; acetone 99.7 wt%; ethanol 95 wt%	5.3 MJ/kg butanol (37.54% of conventional distillation)	-	Simulation	Not tested on FW broth	Transferable	(Chen et al., 2018)
ABE broth, 200 g/L substrate (non-FW)	ABE	-	Extraction-based hybrid; direct steam distillation	Recovery efficiency 0.53-0.57 (baseline)	-	6.4-8.3 MJ-fuel/kg ABE	Lowest total annualised cost: in situ recovery, DSD, mixture extraction	Simulation	Extractant regeneration	Transferable	(Díaz and Tost, 2017)
Aqueous butanol (model)	n-Butanol	None	Pervaporation, PDMS/ZIF-8 membrane	Flux +350% vs neat PDMS	Selectivity +6% vs neat PDMS	-	-	Laboratory	Model solution only	Transferable	(Zamani et al., 2023)
Aqueous lactic acid (model)	Lactic acid	None	Adsorption on hyper-crosslinked polymer	High uptake and selectivity (qualitative)	Gypsum-free product	Avoids gypsum-forming precipitation	-	Laboratory	Model solution only	Transferable	(Rübenach et al., 2019)
Municipal biowaste fermentation broth	Lactic acid (PLA grade)	Separate pretreatment of food and lignocellulosic fractions	Reactive distillation; emulsion liquid membrane	-	Sufficient for PLA production	-	-	Laboratory (review)	Rate-limiting hydrolysis of recalcitrant fraction	Demonstrated	(Thygesen et al., 2021)
Sewage sludge + FW fermentate	VFAs to PHA and esters	Co-fermentation	NF/RO; membrane contactor; ion exchange	-	-	-	-	Conceptual	Not validated	Conceptual	(Owusu-Agyeman et al., 2023)
Mixed FW with impurities	Slurry to CH4; solids to bio-oil	Mechanical slurry-solid separation	Slurry-solid split before AD and pyrolysis	BMP 572.88 vs 294.37 mL/g VS (whole FW)	Bio-oil N compounds -62%	2.8-3.8 times lower energy demand than alternatives	NPV US$15 million; IRR 34%	Laboratory + TEA model	-	Demonstrated	(Okopi et al., 2024)
Biogas from FW digestion	Biomethane	None	In situ biological methanation (H2 + biochar)	722 mL CH4/g VS	CO_2 removal 39.5%	Exogenous H2 (88.0% utilisation)	-	Laboratory	Hydrogen supply	Demonstrated	(Li and Kobayashi, 2025)

Table 4. Techno-economic indicators reported for food-waste valorisation systems. Values are as reported (currency and base year of the original study); they are not normalised and should not be compared directly across rows.

FW feedstock to product(s)	Scale / capacity	Capital / operating cost	Revenue or price assumption	NPV / net profit	IRR / ROI	Payback	Key sensitivity	Basis	Source
FW to plasticiser + lactic acid (Scenario I)	1 t/d; 20 y	-	-	NPV US$3,028,000; net profit US$422,699/y	IRR 18.98%	7.56 y	Lactic acid price	Simulation	(Kwan et al., 2015)
FW to plasticiser + animal feed (Scenario II)	1 t/d; 20 y	-	-	Deficit US$42,632/y	-	-	-	Simulation	(Kwan et al., 2015)
FW to lactic acid (non-sterile)	Catchments 50,000-1,000,000 inhabitants	-	-	Profitable at ≥200,000 inhabitants	-	-	Catchment size	Laboratory data + model	(Peinemann et al., 2019)
FW to fuel ethanol	10 t/d; 15 y	Capital US$367,552;	Ethanol price; FW treatment fee	Net profit US$74,995.57/y	-	5 y (5% discount rate)	Ethanol price; treatment fee	Model	(Chen et al., 2022)

		operating US$155,959/y							
Mixed FW to biogas (AD)	Case study	-	Break-even US$0.2944/m³	NPV US$3108 at US$0.39/m³	-	6 y (discounted)	Biogas price; waste-fee savings	Laboratory data + model	(Al-Wahaibi et al., 2020)
FW with impurities to CH4 (slurry) + pyrolysis products (solids)	-	-	-	NPV US$15 million	IRR 34%	-	-	Laboratory data + model	(Okopi et al., 2024)
OFMSW to on-site enzymes + SSF biopesticide (+AD)	-	-	Profit margin 74%	-	IRR 13%	6 y	Enzyme price; AD efficiency	Model	(Molina-Peñate et al., 2024)
Fish and mollusc residues to protein hydrolysate, CaCO3, biochar	-	Hydrolysate production 72.5-83.8% of OPEX	Hydrolysate €2/kg; revenue €955.1/t (fish)	-	-	2.9 y (fish)	Hydrolysate selling price	Model	(Andreola et al., 2023)
FW + glucose + oleic acid to sophorolipids	Hong Kong; 4 scenarios	-	-	Feasible in all scenarios	-	-	Equipment origin; product form; 7% discount rate	Model	(Wang et al., 2020)
Vegetable waste to bio-oil, biochar (pyrolysis)	14 simulated scenarios	-	-	-	ROI 29%	3.4 y	Temperature; moisture	Simulation	(Alherbawi et al., 2024)
FW digestate to biochar (HTC + post-carbonisation)	20 kt/y plants	-	-	-	-	-	Gate fee	Model	(Gamaralalage et al., 2025)
FW-derived VFAs to denitrification carbon	Engineering-scale scenario	>70% reduction in long-term carbon cost	-	-	IRR 8.5%	-	Monte Carlo (n = 100,000)	Laboratory data + model	(Zheng et al., 2025)
Tomato, potato, orange, olive processing wastes to multiple products	EU-level screening	Screening estimates	-	-	ROI (values - in abstract)	-	Number and size of plants vs logistics	Screening model	(Cristóbal et al., 2018)
Household FW to AD, composting, incineration, landfill (life-cycle cost)	UK, 4.9 Mt/y	Incineration £71/t; landfill £123/t	-	-	-	-	-	LCA/LCC model	(Slorach et al., 2019)

Table 5. Life-cycle evidence for food-waste valorisation pathways. GWP, global warming potential; PE, polyethylene; LCC, life-cycle cost.

System compared	Functional unit	Climate result	Other reported results	Hotspots / determinants	Basis	Source
AD, in-vessel composting, incineration, landfill (UK household FW)	Per tonne of FW treated	AD net-negative GWP	AD lowest in 13 of 19 categories; in-vessel composting least sustainable	-	Model (LCA + LCC)	(Slorach et al., 2019)
Wet and dry pig feed vs AD and composting (UK)	-	-	Wet feed best in 13 of 14 and dry feed in 12 of 14 categories	Substitution of conventional feed	Hybrid consequential LCA	(Salemdeeb et al., 2017)
BSF treatment vs windrow composting (Indonesia)	1 t biowaste (wet weight)	Composting GWP double that of BSF; direct CO2-eq 47 times lower for BSF	-	Residue post-composting (69% of BSF GWP); electricity	Field gas measurements + LCA	(Mertenat et al., 2019)
HTC-AD vs AD vs landfill (Kampala market FW)	-	≈96% reduction for most categories' vs landfill	Landfill diversion 91% (HTC-AD) vs 75% (AD); energy efficiency 69% vs 45%	-	Process model + MFA + LCA	(Somorin et al., 2023)
Mixed-culture PHA pilot vs PE	-	GWP more than 5 times earlier literature values	Fossil depletion 10.30- and 7.59-times PE (two scenarios)	Isolated plant; benefit only within resource-energy-water union	Pilot field data	(Wu et al., 2023)
Fungal food from surplus bread (four inoculation scenarios)	-	-	Back-slopping scenario lowest impacts; protein 25-29%	Inoculum production; solid-state fermentation	Laboratory data + LCA	(Brancoli et al., 2021)

FW digestate biochar applied to soil (UK)	Per tonne of biochar	Net -1.15 to -1.20 t CO2-eq	Durable carbon storage 1.7 t CO2-eq/t	Digestate transport; fossil-fuel use	Model (TEA + LCA)	(Gamaralalage et al., 2025)
Pyrolysis of vegetable wastes (14 scenarios)	-	-	Water footprint increased with temperature; land footprint constant	Temperature; feedstock moisture	Simulation	(Alherbawi et al., 2024)