

Review

Food Waste Valorization: Guidance for Integrating Sustainable Management Strategies

Rendra Hakim Hafyan ¹, Vinod Kumar ², Sunil K. Maity ³, Jhuma Sadhukhan ^{4,5}  and Siddharth Gadkari ^{1,4,*}

¹ School of Chemistry and Chemical Engineering, University of Surrey, Guildford GU2 7XH, UK; r.hafyan@surrey.ac.uk

² Magan Centre for Applied Mycology, Cranfield University, Cranfield MK43 0AL, UK; vinod.kumar@cranfield.ac.uk

³ Department of Chemical Engineering, Indian Institute of Technology Hyderabad, Kandi, Sangareddy 502284, Telangana, India; sunil_maity@che.iith.ac.in

⁴ Institute for Sustainability, University of Surrey, Guildford GU2 7XH, UK; j.sadhukhan@surrey.ac.uk

⁵ School of Engineering, University of Surrey, Guildford GU2 7XH, UK

* Correspondence: s.gadkari@surrey.ac.uk

Abstract

Food waste (FW) is a major global challenge with significant economic and environmental costs, yet its nutrient-rich composition also offers an opportunity for valorization into high-value biochemicals and biofuels within a circular bioeconomy. Effective FW management requires systematic frameworks that balance environmental performance, economic returns, and social acceptance, a challenge that is particularly difficult in developing countries where technical, financial, and participation barriers persist. This review proposes a strategic, step-by-step approach to enhance current FW management through the objective integration of biorefinery pathways producing biochemicals and biofuels products. Both biochemical and thermochemical conversion routes are evaluated against industrial yield benchmarks, market value, and end-use specifications to identify the products and processes most capable of enhancing sustainability. The review further presents a framework for multi-objective optimization (MOO) that simultaneously addresses economic, environmental, and social objectives, and for incorporating decision-maker preferences into the selection of optimum solutions. By coupling sustainability assessment with structured decision support, this review provides practical guidance for selecting FW management strategies that are economically viable, environmentally sound, and socially acceptable.

Keywords: food waste; food waste management; sustainability assessment; circular bioeconomy; decision making



Academic Editor: Silvia Tabasso

Received: 3 April 2026

Revised: 12 May 2026

Accepted: 21 May 2026

Published: 26 May 2026

Copyright: © 2026 by the authors.

Licensee MDPI, Basel, Switzerland.

This article is an open access article distributed under the terms and conditions of the [Creative Commons Attribution \(CC BY\)](https://creativecommons.org/licenses/by/4.0/) license.

1. Introduction

As the global population is projected to reach 9.6 billion by 2050, ensuring food security within the constraints of available resources is expected to become increasingly challenging [1]. The majority of food consumed is either lost or wasted at various stages of its supply chain, including primary production, manufacturing, distribution and consumption by the end user [2]. Globally, an estimated 1.05 billion tonnes of food are discarded annually [3]. The substantial amount of FW globally leads to significant economic, environmental, and biodiversity challenges [4,5]. It is estimated that globally FW causes an economic loss of \$990 billion and results in 4.4 gigatons of CO₂-eq emissions [6]. In the European Union, 88 million tons of food are wasted annually, generating 170 million tons

of CO₂-eq emissions [7]. In the UK, approximately 43 million tonnes of food are purchased annually, primarily for household consumption, yet nearly one-quarter is wasted across the supply chain. Of this, 71% of post-farm gate waste is edible (around 6.4 million tonnes), resulting in an estimated economic loss exceeding £21.8 billion and generating at least 18 million tonnes of greenhouse gas (GHG) emissions each year [8].

These issues have led to the implementation of policies such as the UN's SDG 12.3, aiming for a 50% reduction in FW by 2030 [9]. The circular bioeconomy is expected to reduce EU GHG emissions by 55% by 2030, with potential savings of 3.5 million tonnes of CO₂-eq [10]. The UK government has set a target to reduce FW by 50% by 2030 and achieve 65% waste recycling by 2035, contributing to the broader goal of net zero by 2050 [11,12]. To address the growing FW issue, international policies have focused on reducing landfill disposal. The European Union's Landfill Directive mandates the reduction of organic waste sent to landfills [13], and the UK aims to eliminate biodegradable waste from landfills by 2028, with separate FW collections starting in 2025 [14]. In fact, around 90% of FW can be recycled into valuable products, helping to create economic opportunities and reduce environmental impact [15].

Given its rich nutrient content, including carbohydrates, proteins, and fats [16], FW is an ideal feedstock for biorefinery processes, capable of producing valuable and sustainable products [15,17]. This approach contributes to a circular bioeconomy, maximizing the potential of FW and supporting eco-friendly innovations [18]. Recent studies of techno-economic analysis (TEA) and life cycle assessment (LCA) reveal that FW valorization offers significant economic and environmental benefits. Hafyan, et al. [19] reported that integrated biorefineries utilizing bread waste (BW) for bioethanol and succinic acid production achieve high economic performance (internal rate return (IRR) 33%, net present value (NPV) 163 M\$, and 2.2 year payback period (PBP)) alongside net-negative carbon emission (−0.344 kgCO₂-eq/kg BW). Rajendran and Han [20] revealed that poly(butylene succinate) (PBS) from FW was economically feasible (NPV 58.88 M\$, IRR 16.48%, and PBP 6.33 years) and environmentally favorable, with GHG emissions of 5.19 kg CO₂-eq/kg PBS, lower than conventional PBS production. Li, et al. [21] evaluated an integrated system for producing volatile fatty acids (VFA) from FW, resulting in a production cost of 3.12 \$/kg VFA and net-negative GHG emissions of −0.4 kg CO₂-eq/kg VFA.

While the previous TEA and LCA studies demonstrate that FW valorization can provide significant economic and environmental benefits through production of marketable products. These benefits can be further enhanced by integrating current FW management routes with biorefinery systems that co-produce biochemicals, biofuels, and energy, thereby improving economic, environmental and social sustainability. Several reviews have approached different aspects of this integration. Santagata, et al. [22] reviewed FW conversion within a circular economy framework, highlighting the need for policy and technological support to enable large-scale implementation. Using LCA and energy analysis, the study assessed the environmental performance of FW treatment pathways in the EU and developed a classified database of conversion systems. The results indicate that biological and mixed-waste conversion routes offer advantages in terms of reduced environmental impacts, improved resource efficiency, economic value, and job creation. Lenka, et al. [23] review showed that conventional FW management methods such as landfilling and incineration are still widely used despite causing significant environmental impacts. While standalone conversion technologies (e.g., anaerobic digestion (AD), pyrolysis, gasification, and fermentation) can recover energy and materials, they often suffer from limited efficiency and scalability; therefore, integrated valorization systems are recommended to improve resource recovery and enable the production of high-value products such as biofuels and hydrogen-rich syngas within a circular bioeconomy framework. Arvelli, et al. [24] compared FW valorization of thermochemical,

biological, and green-extraction routes, finding that high-value platform chemicals (organic acids, phenolics) offer greater economic potential than biofuels, and proposed AI/ML/IoT integration to address scale-up and efficiency limitations of smart biorefineries. Collectively, these reviews demonstrate that FW valorization into high-value, marketable products represents a promising route to enhance sustainability, and that integrating valorization with conventional FW management can further amplify these benefits. Hafyan, et al. [25] reviewed bread waste valorization pathways for producing biofuels and platform chemicals, assessing their performance across economic, environmental, and social dimensions. The study highlights process integration as the key driver of sustainability improvement. In particular, coupling biochemical conversion with anaerobic digestion, heat recovery steam generator (HRSG), and carbon capture and utilization enables effective recovery of mass, energy, and carbon streams. This integrated approach significantly enhances both environmental and economic performance, supporting the system-level integration concept. However, none of them has explicitly addressed how such integration can be formalized through mathematical optimization that simultaneously balances economic, environmental, and social objectives, nor how decision-making approaches incorporating stakeholders' preferences can be applied to identify the most sustainable configuration. To bridge this gap, the present work proposes a unified framework that couples MOO with multi-criteria decision-making (MCDM), enabling the integrated FW management–biorefinery system to be designed not only for technical and economic feasibility but also for environmental performance and social acceptability, thereby advancing both the methodological and practical foundations of sustainable FW management.

To address these gaps, future research should explore potential products from FW valorization and how it can be integrated into current FW management practices. This integration aims to enhance resource efficiency and overall system sustainability by improving energy and waste use. Adopting such strategies can support economically, environmentally, and socially responsible decision-making. The insights from this review offer valuable guidance for policymakers in selecting suitable FW management technologies. The paper is structured into nine sections. Section 1 introduces the topic and outlines its importance. Section 2 defines FW, while Section 3 discusses FW generation and composition in detail. Section 4 explores the potential products derived from current FW management practices. Section 5 delves into FW valorization, examining the biochemical and thermochemical production. Section 6 proposes an integrated sustainability strategy for FW biorefineries, focusing on sustainability assessments and strategic approaches. Section 7 addresses the challenges associated with FW valorization, and Section 8 outlines decision-making approaches for selecting FW management strategies, covering both conventional FW management and biorefinery technologies. Finally, Section 9 concludes the paper with a summary of the findings and implications.

2. Food Waste Definition

Food waste is a major global issue with significant environmental, economic, and social implications, and a clear conceptual framework is essential for its analysis. Although terminology varies across organizations, the definitions provided by FAO, the European Commission, and WRAP consistently distinguish food loss from FW based on supply chain stages. According to the FAO, food loss and waste refer to reductions in the quantity or quality of food along the supply chain, where food loss occurs during production, post-harvest handling, and processing, while FW occurs at retail, food service, and consumer levels [26]. The European Commission defines food loss as the reduction of food quantity or quality before it reaches consumers, including food that is discarded and does not re-enter the supply chain, whereas FW refers to food intended for human consumption that is ultimately not eaten and discarded, either intentionally or unintentionally [27].

Similarly, WRAP defines food loss as food not harvested or lost during production, while FW includes both edible and inedible food discarded or sent to disposal routes such as landfill, incineration, or sewer systems [28]. Despite these differences in wording, all three frameworks align in distinguishing upstream losses from downstream waste. Food loss generally occurs at early supply chain stages due to technical, logistical, or infrastructural constraints, whereas FW is mainly associated with retail, food service, and consumer behavior [29]. FW can further be classified into avoidable waste (edible food that could have been consumed) and unavoidable waste (inedible fractions such as bones, eggshells, and fruit peels generated during preparation) [30].

3. Food Waste Generation and Composition

The latest Food Waste Index Report (2024) by UNEP identifies households as the leading source of global FW, contributing 60% of the total, followed by the food service sector at 28% and retail at 12% [3]. Similarly, WRAP [28] reports that UK households generate 60% of FW, with the remaining contributions from on-farm activities (15%), manufacturing (13%), hospitality and food service (10%), and retail (2%). Figure 1 illustrates global per capita household FW in kilograms on an annual basis. These findings highlight the central role of households in the global FW problem and underscore the importance of targeted strategies at the consumer level. Household FW is often driven by behavioral factors, such as poor leftover management and excessive purchasing [31].

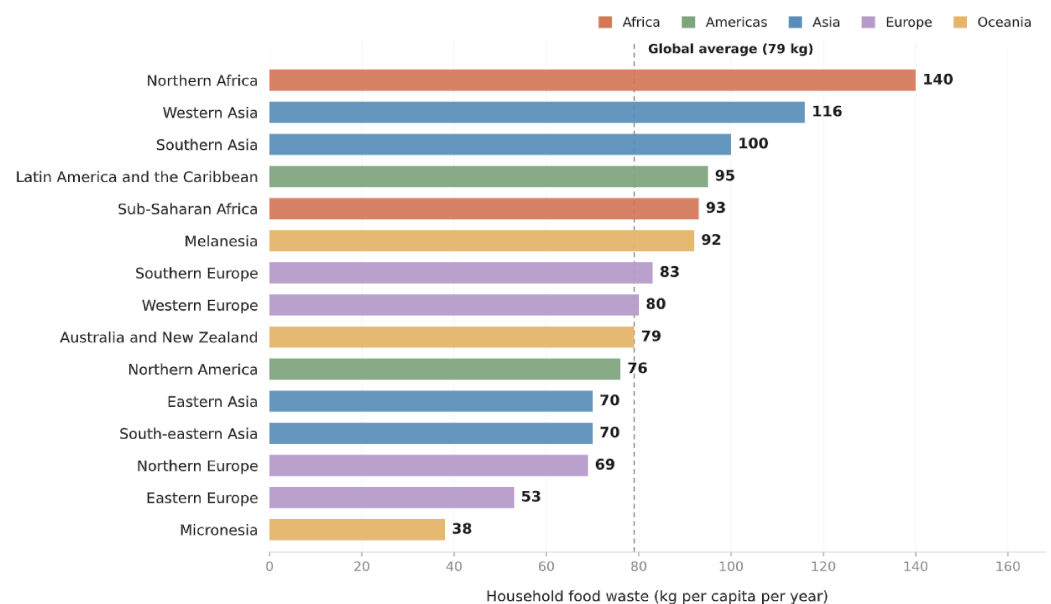


Figure 1. FW generation at household level per kg per capita per year, UNEP [3].

The composition of FW varies by factors such as geographical location, culture, economic status, population density, and dietary habits [32]. For instance, potatoes are a common carbohydrate source in northern Europe, while pasta is favored in the Mediterranean, and rice in South and Southeast Asia. Protein sources also differ, with livestock prevalent in central Europe, fish in the Pacific Rim, and eggs and pulses in parts of India [33]. In Malaysia, rice is the most wasted food, while in Europe and East Asia (e.g., Japan, China, and South Korea), vegetables and fruits make up the largest portion of waste at 40% and 56%, respectively [32]. Restaurant waste mainly consists of carbohydrates, such as rice, noodles, and vegetables, along with oil, eggs, meat, and other waste [34]. In the UK households, typical waste includes meat, fish, dairy, vegetables, fruits, bakery items, meals, and others, with fresh vegetables and fruits accounting for around 20% of the total, a pattern

seen across much of Europe [33,35]. In addition, WRAP [28] identifies the top ten most wasted foods in UK homes as potatoes, meals, bread, milk, poultry, mixed vegetables, cakes, pork/ham/bacon, processed potatoes, and salads.

In essence, macronutrients, vital nutrients required in large amounts, are present in FW and can be broadly categorized into carbohydrates (30–60%), proteins (5–10%), and lipids (10–40%) on a dry weight basis [36,37]. Table 1 summarizes data from various sources to illustrate FW composition, offering insights into the types of foods wasted and their nutritional profiles. The analysis includes mixed FW from kitchens, canteens, households, and restaurants, as well as specific items like potatoes (raw, sweet, chips, peels), bread and bakery products, fruits (e.g., papaya, banana, orange), vegetables (e.g., lettuce, spinach), meat (beef, chicken, pork), and fish. Bakery waste has the highest carbohydrate content (avg. 53.17%, SD = 13.88), followed by mixed FW (41.87% $\pm$ 15.56), while fruits (13.51%) and vegetables (8.27%) contain much less. As expected, meat and fish have negligible carbohydrates. Protein is most concentrated in fish (19.29%) and meat (18.33%), with mixed FW showing moderate levels (16.57% $\pm$ 6.91), and fruits (1.53%) and vegetables (2.09%) having the least. Lipids are most abundant in mixed FW (20.08%) and meat (7.83%), with notable variability, while fish has moderate levels (2.33%) and fruits (0.99%) and vegetables (0.42%) the lowest. Overall, FW is predominantly rich in carbohydrates, especially from bakery waste, mixed FW, potatoes, fruits, and vegetables, while meat and fish contribute significantly to protein and lipid content [38]. The broad range and high standard deviations reflect considerable variability in FW composition, which is important for its suitability in biorefinery processes and FW valorization strategies.

Table 1. Percentage of macronutrients composition contained in FW (wet basis).

Food Category	Samples	Food Composition						Ref.
		Carbohydrate (%)		Protein (%)		Lipid (%)		
		Mean ± SD	Min–Max	Mean ± SD	Min–Max	Mean ± SD	Min–Max	
Mixed FW	<i>n</i> = 12	41.87 ± 15.56	16.90–69.51	16.57 ± 6.91	3.40–29.60	20.08 ± 8.42	3.80–33.82	[39–45]
Potato	<i>n</i> = 16	26.03 ± 13.12	12.4–64.83	2.65 ± 1.93	1.20–9.46	4.08 ± 7.06	0.05–24.7	[46–50]
Bakery waste	<i>n</i> = 10	53.17 ± 13.88	37.42–86.04	10.58 ± 2.90	7.32–15	11.34 ± 13.14	0.40–35.32	[51–55]
Fruits ^a	<i>n</i> = 46	13.51 ± 8.63	3.10–40.12	1.53 ± 1.65	0.20–8.60	0.99 ± 2.25	0.10–14.70	[56–59]
Vegetables ^a	<i>n</i> = 34	8.27 ± 8.28	0.40–34.60	2.09 ± 1.35	0.30–6.40	0.42 ± 0.23	0.10–1.10	[60–62]
Fish	<i>n</i> = 19	-	-	19.29 ± 1.89	15.61–21.80	2.33 ± 1.79	0.81–8.60	[63–65]
Meat	<i>n</i> = 16	2 ± 2.27	0–8	18.33 ± 2.81	14.10–22.20	7.83 ± 6.84	1.10–26.40	[66–68]

Note: ^a some data taken from the United States Department of Agriculture (USDA).

4. Food Waste Management Practice

The growing issue of FW poses significant sustainability challenges, prompting governments worldwide to implement diverse strategies aligned with global objectives such as the United Nations' Sustainable Development Goals focusing on reducing waste, promoting recycling, and encouraging sustainable consumption. In the U.S., the Environmental Protection Agency (EPA) and the USDA aim to halve FW by 2030 through programs that promote food recovery, sustainable food management, and reduced landfill use [69]. Australia's National Waste Policy supports local governments in collection, recycling, and public education initiatives [70]. Asia showcases varied approaches: Japan's Food Waste Recycling Law mandates recycling targets for food-related industries and mandates large waste generators to report annual FW data [71]; In Singapore, the National Environment Agency (NEA) and AgriFood and Veterinary Authority (AVA) run educational campaigns encouraging better food storage, meal planning, and leftover use [72]; South Korea enforces a Volume-Based Waste Fee (VBWF) system where households pay based on waste volume using standardized bags [73]; China's "zero-waste city" policy promotes recycling and resource recovery in line with circular economy principles [74]. In Europe, the EU waste

management framework prioritizes waste handling in descending order: prevention, reuse, recycling, energy recovery, and disposal [75]. The UK has adopted this hierarchy to manage surplus food and drink waste, favoring actions like source reduction, use as animal feed, AD, and composting, while minimizing reliance on incineration and landfilling [76], as depicted in Figure 2. Source reduction remains the most environmentally beneficial strategy, yielding the lowest greenhouse gas emissions [77,78].

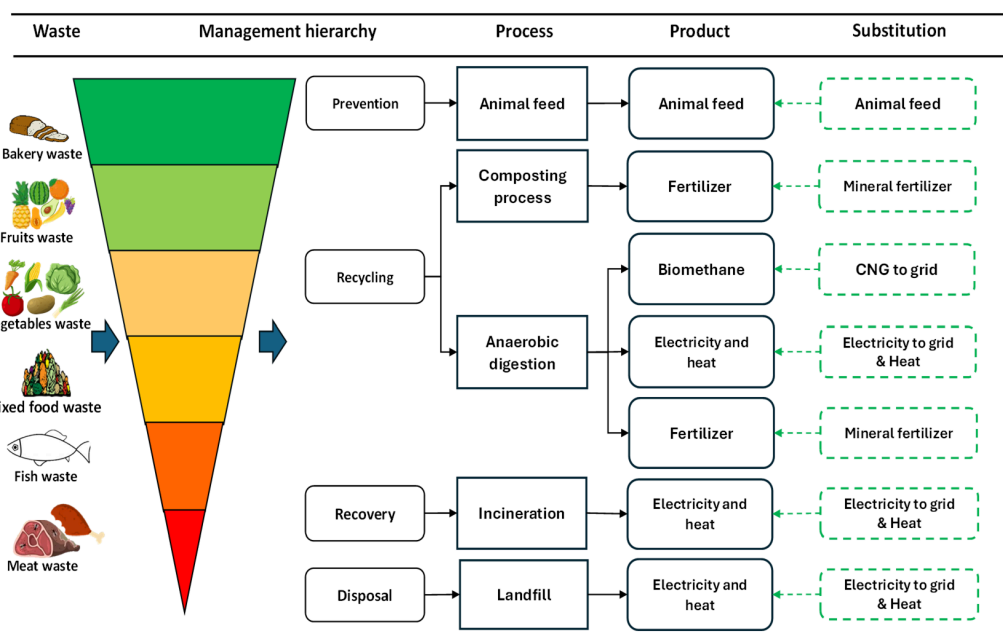


Figure 2. Current FW management hierarchy.

FW, rich in organic matter, nutrients, and minerals, holds significant potential as a feed-stock for animal nutrition, offering a sustainable way to reduce FW volume [79]. Several studies have demonstrated its successful conversion into feed for livestock such as dairy cattle [80], pigs [81], fish [82], and chickens [83]. Composting is another biological strategy that supports nutrient recovery and carbon sequestration through the formation of humic substances [84], reducing fertilizer demand, enhancing crop yields, and diverting organic waste from landfills [85]. AD offers a versatile solution for FW valorization by producing biogas and nutrient-rich digestate, suitable for heating, electricity, bio-compressed natural gas, and biofertilizers [86,87]. Although, less favorable environmentally, incineration and landfilling also yield by-products with potential value. Waste-to-Energy (WtE) incineration can reduce waste volume by up to 85%, with over 2000 plants globally [88,89]. These facilities convert municipal solid waste (MSW) [90], green waste [91], wastewater treatment plant sludge (WWTPs) [92], and industrial waste [93] into electricity and heat [88]. However, incineration may generate air pollutants (e.g., particulate matter, NO_x, dioxins, and heavy metals), requiring advanced flue gas treatment and emission control systems to comply with stringent environmental regulations [94]. Meanwhile, landfilling, still widely used, presents environmental concerns including odor, fires, volatile organic compounds (VOCs), groundwater pollution, and methane emissions [95]. To mitigate these impacts, modern sanitary landfills employ liners, leachate collection systems and landfill gas capture technologies [96]. The landfill gas (LFG), composed primarily of methane and carbon dioxide, can be captured and utilized for energy generation, particularly heat through cogeneration systems [97].

Table 2 summarizes the product substitutions generated by various FW treatment technologies, considering both economic and environmental aspects. Among the current

FW management practices, composting and AD stand out as the most cost-effective options. This is due to their simpler processes, which result in lower investment costs and higher revenue. In terms of environmental impact, AD is notable for its low environmental footprint per ton of FW generated, largely because of the energy recovery from its products. Similarly, animal feed, composting, and AD also exhibit low GWP, owing to their minimal chemical, energy consumption and higher credit impact. Conversely, incineration and landfilling are associated with the highest environmental impacts. Several studies have further compared the environmental impacts and economic assessments of different FW management practices, reinforcing these findings. Eriksson, et al. [78] and Vandermeersch, et al. [98] suggested that FW-based animal feed had low environmental impacts, while AD and incineration were optimal for energy recovery, Alsaleh and Aleisa [99] contradicted this, finding that incineration had the lowest environmental impact. However, most studies consistently favored AD for its lower GWP and environmental impact compared to incineration and landfilling [100–102]. Moreover, Slorach, et al. [103] projected that AD, particularly when upgrading biogas to biomethane, would offer the best environmental and economic sustainability among FW treatment methods, potentially resulting in net-negative GWP if integrated with other energy sources. Even though, these current FW management practices have offered some benefits in terms of economic and environmental point of view. The incinerators should be equipped with advanced emission control systems due to the stringent flue gas emissions standard in place. The landfill of FW is facing growing pressure due to limited land availability. Thus, both incineration and landfill of FW should not be considered as a sustainable approach for future FW management [104]. Nowadays, the central objective of FW management is how to maximize energy and resource recovery with minimal environmental impact. In this instance, AD, compost production appear to be the most promising technologies, and animal feed for FW management, which can help to substantially relieve the burdens on incineration and landfilling.

Table 2. The economic and environmental performance of FW management options.

Feedstock	FW Management Option	Technology	Product	Economic Value			Environmental Impact (kg CO ₂ -eq/t Feedstock)	Reference
				Investment (M\$/t Feedstock)	Production Cost (M\$/t Feedstock)	Revenue (M\$/t Feedstock)		
FW	Animal feed	Dry process	Dry pallet feed	-	-	-	-28.3	[105]
FW	Animal feed	Dry process	Dry pig feed	-	-	-	39.6	[106]
FW	Animal feed	Wet process	Wet pig feed	-	-	-	2.09	
FW	Composting	Composting	Fertilizer	-	-	-	-936.6	[105]
FW	Composting	Composting	Fertilizer	0.017	0.01	0.017	-	[107]
FW	Composting	Top soil pot	Fertilizer	* 0.08	* 0.042	* 0.007	-	[108]
Organic FW	Composting	Windrow composting	Fertilizer	-	** 29.94	** 69.85	1.52	[109]
FW	Composting	Open-air static pile	Fertilizer	0.081	0.024	0.018	-402.9	[110]
FW	AD	Fermentation	Biomethane	-	-	--	-61.8	[105]
FW	AD	Methane upgrading	Biomethane	0.033	0.008	0.014	-37.7	[111]
FW	AD	CHP	Electricity & heat	0.038	0.0078	0.0017	-193.5	
FW	AD	Methane upgrading	Biomethane	0.0302	0.0051	0.0042	-219.9	[112]
FW	AD	CHP	Electricity & heat	0.0303	0.0017	0.0063	-289.1	
FW	AD	CHP	Electricity	0.05	0.011	0.021	0.036	[113]
FW	Incineration	Combustion	Electricity	-	-	-	284	[105]
^a MSW	Incineration	Combustion	Electricity	0.092	0.0037	0.0004	-	[114]
FW	Incineration	CC	Electricity	-	-	-	107	[115]

Table 2. Cont.

Feedstock	FW Management Option	Technology	Product	Economic Value			Environmental Impact (kg CO ₂ -eq/t Feedstock)	Reference
				Investment (M\$/t Feedstock)	Production Cost (M\$/t Feedstock)	Revenue (M\$/t Feedstock)		
^a MSW	Incineration	MGC	Electricity	0.0356	0.0014	^b −0.0009	-	[116]
^a MSW	Incineration	CFBC	Electricity	0.0409	0.0016	^b −0.0082	-	
^a MSW	Incineration	Combustion	Electricity	0.229	0.567	^b −0.584	-	[117]
^a MSW	Incineration	CHP	Electricity & heat	-	-	-	58	[118]
^a MSW	Landfill	CHP	Electricity & heat	-	-	-	223	
FW	Landfill	CHP	Electricity & heat	-	-	-	565.3	[105]
^b Organic waste	Landfill	CHP	Electricity & heat	0.0034	0.00047	^b 0.129	3860	[119]

Note: * RM: ringgit Malaysia; ** MSAR: million Saudi riyal; CHP: combined heat and power; CC: combined cycle; ^a msw: municipal solid waste (with major portion of FW); ^b data taken from one big Colombian cities (Bogota) and revenue is NPV data; MGC: moving grate combustion; CFBC: circulating fluidized bed combustion.

5. Food Waste Valorization

FW generated at various supply chain sites is often disposed of through landfilling or incineration without proper treatment, leading to severe environmental consequences [120]. Incineration releases harmful by-products such as ash and flue gases that pose respiratory risks [121], whereas landfilling generates toxic leachates that contaminate groundwater and emits hazardous gases including methane and hydrogen sulfide [122]. These environmental concerns highlight the urgent need for sustainable FW management strategies. In this context, FW valorization into value-added products has emerged as a promising approach aligned with circular bioeconomy principles [123], reducing reliance on fossil-based raw materials. Due to its nutrient-rich composition, FW is increasingly recognized as a suitable feedstock for biorefineries producing chemicals, materials, and biofuels [124,125]. This approach not only reduces the amount of organic waste requiring disposal but also decreases dependence on petroleum-derived resources [126] while supporting the United Nations Sustainable Development Goal 12 on responsible consumption and production [127]. As shown in Figure 3, FW can be valorized through two main pathways: biochemical conversion, which employs microbial fermentation or enzymatic processes to produce high-value chemicals and fuels, and thermochemical conversion, which uses elevated temperatures and pressures to convert FW into bio-oil, biochar, syngas and other energy products. The following sections discuss these pathways with emphasis on process performance, industrial relevance, and integrated biorefinery applications.

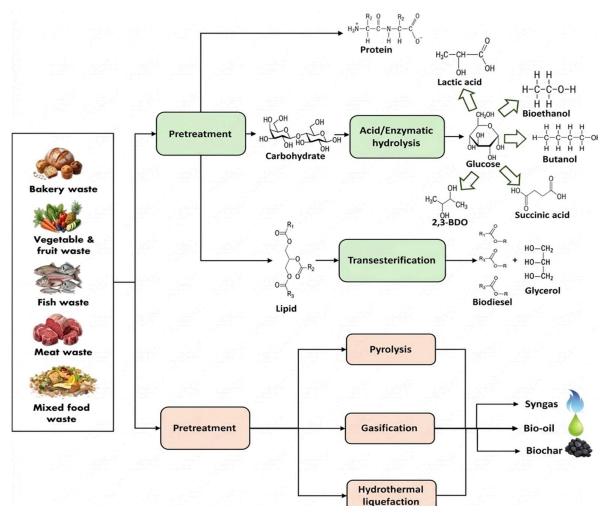


Figure 3. Potential FW-based biochemical and thermochemical production.

5.1. FW-Based Biochemical Conversion

5.1.1. Pretreatment

Pretreatment of FW is a critical step in unlocking its macronutrient fractions for downstream conversion, and typically involves a combination of physical, thermal, and chemical or enzymatic processes. Mechanical pretreatment, including grinding or milling, is typically the initial step used to reduce particle size (0.5–2 mm) [128], thereby increasing surface area and enhancing organic matter solubilization [129]. The pretreated FW is then subjected to hydrolysis to liberate fermentable sugars from complex carbohydrates, with the choice of hydrolysis route determining the subsequent processing sequence. Acid hydrolysis using dilute H_2SO_4 or HCl is typically performed at elevated temperature (121 °C in an autoclave for 5 to 30 min) with acid concentrations 0.5 to 2% *v/v*, enabling simultaneous sugar release and microbial inactivation in a single process step [130]. Enzymatic hydrolysis using α -amylase, glucoamylase, and cellulase mixtures is typically conducted under mild conditions (50–60 °C) and therefore requires prior sterilization, commonly by autoclaving to inactive endogenous microorganisms and improve enzyme accessibility through partial starch gelatinization [51]. Among the two routes, enzymatic hydrolysis is the most widely adopted approach for FW given its high yield, mild operating conditions, less environmental emission, and minimal inhibitor formation, making it directly compatible with subsequent microbial fermentation [131]. Both studies by Narisetty, et al. [51] and Narisetty, et al. [132] reported that enzymatic hydrolysis of bread waste produced higher bioethanol and BDO titers (114.9 and 138.8 g/L, respectively) than acid hydrolysis (106.9 and 135.4 g/L, respectively).

5.1.2. Macronutrient Extraction and Fractionation

Table 3 presents an overview of pretreatment methods employed to extract macronutrient components from FW. Carbohydrates within FW are typically hydrolyzed via enzymatic or acid-based processes. These pretreatments are designed to modify the structural properties of FW, thereby increasing enzymatic accessibility and facilitating the breakdown of complex carbohydrates into fermentable sugar monomers [133]. The primary objective of this stage is to induce molecular alterations that enhance the efficiency of subsequent bioconversion processes [134]. Following pretreatment, the liberated carbohydrate polymers undergo enzymatic hydrolysis to yield simple sugars, which act as precursors for the synthesis of value-added bio-based chemicals and fuels. This conversion is generally achieved through a sequential combination of chemical and enzymatic hydrolysis, ensuring the efficient release of fermentable sugars. Kumar and Longhurst [37] conducted a comprehensive review examining the potential of FW as a feedstock for the production of key chemical building blocks, including lactic acid (LA), succinic acid (SA), 2,3-butanediol (BDO), ethanol, and n-butanol. Their findings underscore the viability of FW, given its high carbohydrate content, as an alternative substrate for microbial fermentation in biorefinery applications. Moreover, the U.S. Department of Energy (DOE) has identified several of these compounds as high-value platform chemicals with significant industrial relevance [135]. Similarly, the UK government, through the E4TECH initiative, has evaluated and prioritized bio-based chemical and fuel products based on their market potential and alignment with national capabilities [136]. For commercial fermentation, industrial competitiveness typically requires yields close to the theoretical maximum: ≥ 0.45 g/g glucose for ethanol [137], ≥ 0.90 g/g for lactic acid [138], ≥ 0.50 g/g for succinic acid [139], ≥ 0.48 g/g for 2,3-BDO [140], and ≥ 0.20 g/g for ABE-derived butanol [141]. The FW-derived yields summarized in Table 3 meet or approach these benchmarks across all five products: ethanol (0.47–0.49 g/g), lactic acid (0.85–0.92 g/g), succinic acid (0.52–0.56 g/g), 2,3-BDO (up to 0.48 g/g), and ABE (up to 0.43 g/g). This indicates that despite FW heterogeneity, microbial

conversion remains effective when hydrolysates replace refined sugars, supporting its use as a low-cost feedstock for high-value bioproducts.

Lipids present in FW offer a promising feedstock for biodiesel production; however, their extraction is necessary due to the complex composition of FW, which includes carbohydrates and proteins. Lipid recovery is commonly achieved through solvent extraction methods utilizing agents such as n-hexane [142], ethanol [143], dimethyl ether [144], and fungal hydrolysis [145,146]. Among these, n-hexane has demonstrated superior extraction efficiency, achieving lipid recovery rates of up to 99.7% [142,147,148]. The isolated lipids can be separated by centrifugation and subsequently converted into biodiesel, or fatty acid methyl esters (FAME), via transesterification. This reaction can be catalyzed by acids [149], bases [150], enzymes [151], and heterogeneous catalyst [152]. Yield of biodiesel is generally affected by temperature, pressure, molar ratio of lipid to methanol, reaction time, type of catalyst and concentration, type of feedstock [151,153]. In addition to lipids, FW is recognized as a valuable source of protein for applications in food and animal feed [154]. Various extraction techniques have been developed, including acid [155], hydrothermal [156], ionic liquid [157], enzymatic [158], ultrasonication [159], alkaline [160], and membrane filtration [161]. Among these, alkaline extraction is most widely adopted due to its operational simplicity, time efficiency, and cost-effectiveness [162].

One of the primary challenges in valorizing FW lies in the effective separation of its three principal macronutrients: carbohydrates, proteins, and lipids. This step is crucial, as each component exhibits distinct physicochemical properties and valorization pathways, necessitating specific extraction and conversion techniques. Efficient fractionation enables the targeted conversion of carbohydrates into chemicals and fuels, while optimizing the recovery of proteins and lipids for high-value applications, contributing to a sustainable and integrated biorefinery approach. Sadhukhan, et al. [163] developed an integrated biorefinery framework for seaweed, demonstrating a hierarchical extraction strategy to recover proteins, sugars, and nutrients. The process involved drying, milling, aqueous suspension, filtration, and centrifugation. The resulting supernatant, containing polysaccharides and proteins, was further separated via ion exchange resins. Polysaccharides were hydrolyzed into monosaccharides, and proteins purified through dialysis, generating distinct product streams and enhancing resource efficiency. Similarly, Rajendran and Han [148] investigated a process for producing polylactic acid and biodiesel from FW. Lipids were initially extracted using n-hexane and recovered via flash evaporation for reuse. The solvent-free oil was processed into biodiesel, while the defatted, carbohydrate-rich residue underwent enzymatic hydrolysis to yield glucose, which was subsequently fermented into lactic acid. This was further purified through ultrafiltration and distillation. The remaining protein-rich residue was repurposed as animal feed, maximizing material utilization. Ladakis, et al. [164] proposed a method for sequentially extracting lipids and proteins from the organic fraction of municipal solid waste (OFMSW), followed by carbohydrate valorization. Lipids were recovered using n-hexane and the solvent recycled via evaporation. The lipid-free stream was treated with NaOH to solubilize proteins, then subjected to filtration, yielding a protein-rich retentate (approximately 90% purity) suitable for drying. The remaining solids were enzymatically hydrolyzed to produce a sugar- and nutrient-rich hydrolysate, used as a fermentation medium for SA production. SA was purified through evaporation, activated carbon decolorization, and crystallization. Although lipids and proteins were effectively recovered, they were not further converted into value-added products in this study.

Table 3. The production of biochemicals and biofuels through microbial processes using FW.

Substrate	Pretreatment	Microorganism/Catalyst/ Solvent	Product	Product Produced (g/L)	Yield (g/g)	Productivity (g L/h)	Reference
Bread waste	Acid hydrolysis	<i>S. cerevisiae</i> KL17	Ethanol	106.9	0.47	2.97	[51]
Bread waste	Enzymatic hydrolysis	<i>S. cerevisiae</i> KL17	Ethanol	114.9	0.49	3.19	
Bakery waste	Enzymatic hydrolysis	<i>Lb. casei</i> Shiota	Lactic acid	94	0.92	2.61	[165]
FW	Enzymatic hydrolysis	<i>Lactobacillus pentosus</i>	Lactic acid	157	0.92	2	[166]
Bakery waste	Enzymatic hydrolysis	<i>Bacillus coagulans</i> DSM1	Lactic acid	155.4	0.85	1.3	[167]
Mixed FW	Enzymatic hydrolysis	<i>Yarrowia lipolytica</i>	Succinic acid	31.7	0.52	0.6	[168]
FW	Enzymatic hydrolysis	<i>Y. lipolytica</i> PSA02004	Succinic acid	87.8	0.56	0.7	[169]
Bakery	Enzymatic hydrolysis	<i>Actinobacillus succinogenes</i>	Succinic acid	47.3	0.55	1.12	[170]
FW	-	<i>Clostridium beijerinckii</i> P260	ABE	18.9	0.38	0.46	[171]
FW	Enzymatic hydrolysis	<i>C. saccharoperbutylacetonicum</i> deltpabuk	ABE	19.65	0.43	1.93	[172]
FW	-	<i>C. beijerinckii</i> P260	ABE	10	0.36	0.49	[173]
Bread waste	Acid hydrolysis	<i>Enterobacter ludwigii</i>	BDO	135.4	0.42	-	[132]
	Enzymatic hydrolysis	<i>Enterobacter ludwigii</i>	BDO	138.8	0.48	-	
Bakery waste	Enzymatic hydrolysis	<i>Bacillus licheniformis</i> YNP5-TSU	BDO	36.7	0.47	0.99	[174]
FW	n-hexane extraction	KOH & Methanol	Biodiesel	-	96.62 ^a	-	[175]
FW	Ethanol extraction	NaOH & Methanol	Biodiesel	-	96.3 ^a	-	[176]
Bakery waste	Fungal hydrolysis	Novozyme-435 & methanol	Biodiesel	-	90 ^a	-	[153]
	Alkaline extraction	NaOH	Protein	-	93.9 ^a	-	[160]
FW	Enzyme extraction	<i>Alcalase</i>	Protein	-	90.6 ^a	-	[158]
Soybean	Ultrasonication	-	Protein	-	84 ^a	-	[159]

yield: ^a wt%; ABE: Acetone, butanol and ethanol.

5.2. FW-Based Thermochemical Conversion

Food waste can be converted into energy carriers and value-added materials through thermochemical processes operating at elevated temperatures and, in some cases, high pressures, without requiring prior macronutrient fractionation. The main thermochemical routes for FW valorization include pyrolysis, gasification, and hydrothermal liquefaction (HTL).

Pyrolysis is the thermal decomposition of FW in an oxygen-free environment at 350–700 °C, producing three principal products, bio-oil, biochar, and pyrolysis gas (syngas), with the relative yields governed by heating rate, residence time, and final temperature [177]. Zaharioiu, et al. [178] demonstrated catalytic pyrolysis of meat and bone meal using mesoporous silica nano catalysts (SBA-3 and SBA-16 with Fe and Ni derivatives) at 450 °C for 1 h, achieving 13.93 wt% bio-oil (HHV 32.56 MJ/kg), 19.06 wt% gas (HHV 46.23 MJ/m³), and 67.01 wt% char on average across the catalysts tested. Fadhil, et al. [179] demonstrated pyrolysis of de-oiled fish waste in a fixed-bed reactor at 500 °C for 60 min with 0.25 mm particles, achieving a maximum bio-oil yield of 57.13 wt% (HHV 37.74 MJ/kg), 20.5 wt% biochar, and 22.4 wt% gas. The bio-oil produced from pyrolysis is generally composed of a diverse range of organic matter, including alcohols, acids, esters, ketones, aldehydes, and phenols [180].

Gasification is a thermochemical process that converts biomass into syngas via partial oxidation under high temperatures, producing a mixture of combustible gases such as hydrogen (H₂), carbon monoxide (CO), carbon dioxide (CO₂), and methane (CH₄) [181]. Among these products, H₂ production has attracted significant attention, particularly from FW, due to its potential as a sustainable energy carrier. Several recent studies have explored this potential. Mirzaei and Tavakoli [182] investigated H₂ production from FW using subcritical and supercritical water gasification. The maximum H₂ yield of 2.44 mmol/g was obtained at 400 °C at 60 min, with a H₂ mole fraction of 29.5% and H₂ selectivity of 41.84% in the absence of catalyst. In contrast, the use of the catalyst CO₃O₄ enhanced the H₂ yield, content and selectivity to 3.36 mmol/g, 36.1%, and 56.49%. Raizada, et al. [183] examined FW conversion using a novel in situ gasification after pyrolysis (IGP) at 700 °C and compared it with conventional overlapping pyrolysis and gasification (OGP). At 0.625 mL/min steam flow, IGP produced higher syngas yield (1.48 vs. 1.31 Nm³/kg) and hydrogen fraction (66.7% vs. 54.5%), with HHV increasing from 12.1 to 17.4 MJ/kg. In

a follow-up study of Raizada, et al. [184] examined FW and its ash as a support for Ni catalyst in gasification at 850 °C. The best performance was achieved using a conventional overlapping process (COP) combined with the catalyst, resulting in highest H₂ fraction and yield with 71.74% and 1.3 m³/kg, respectively. To further improve catalytic performance, Raizada, et al. [185] developed a Ni-based catalyst supported on FW ash (5% and 10% Ni loading) and tested it in steam gasification at 850 °C in a downdraft fixed-bed gasifier. The 5% Ni catalyst performed best, giving higher syngas and hydrogen production than 10% Ni. At a 50% catalyst-to-feed ratio, the syngas yield reached 1.8 m³/kg and the hydrogen fraction increased to 71%, effectively doubling hydrogen yield.

HTL is a thermochemical process that converts wet feedstock into bio-oil using water as the reaction medium under moderate temperature (250–374 °C) at high-pressure (4–22 MPa) [186]. A key advantage of HTL over processes such as fast pyrolysis is its ability to produce lower-oxygen bio-oil [187,188]. Bayat, et al. [189] studied hydrothermal liquefaction (HTL) of FW at 240–295 °C and reported that the best overall product distribution occurred at 240 °C and 30 min. Under these conditions, the process achieved a bio-crude oil yield of 27.5 wt%, with HTL-char and gas yields of approximately 21.7 wt% and 19.6 wt%, respectively. Brilovich Mosseri, et al. [190] investigated HTL of a household FW model in a batch reactor at 280–340 °C. The process produced absolute bio-oil yields of 6.61–29.36 wt%, biochar yields of 12.29–40.73 wt%, aqueous-phase soluble of 13.78–33.98 wt%, and gas yields of 6.15–8.94 wt%. The maximum bio-crude yield (29.36 wt%) was achieved at 272 °C with 2 wt% K₂CO₃, while the highest biochar yield (40.73 wt%) was obtained at 303 °C with 1 wt% K₂CO₃. Bio-oil HHVs ranged from 30.24 to 37.94 MJ/kg with undetectable sulfur, and biochar HHVs were consistently around 31.5 MJ/kg.

Three major products produced from thermochemical processes are bio-oil, biochar, and syngas. Each of these products holds significant potential as a renewable energy carrier or value-added material. Bio-oil is considered a promising liquid fuel use in turbines, engines, boilers, and a wide range of chemicals after upgrading process [177]. Similarly, syngas produced from pyrolysis is used for heat recovery, power generation, and producing chemicals after upgrading [191]. Biochar is a product produced from pyrolysis which is used for carbon sequestration, soil nutrient improvement, and biomass-derived fillers [192]. However, these products in their raw form are not directly suitable for high-value applications, and further upgrading is required to enhance their quality and marketability. Bio-oil typically requires upgrading through processes such as hydrodeoxygenation (HDO) [193], catalytic cracking [194], and steam reforming [195]. Syngas often undergoes cleaning, tar reforming, and gas conditioning to optimize its H₂/CO ratio for downstream synthesis processes [196]. Biochar can also be upgraded through physical or chemical activation to improve surface area and porosity, enabling its use in adsorption, and catalytic applications [197].

6. Food Waste Valorization Integration

The biorefinery concept is increasingly recognized as a sustainable alternative to conventional fossil-based systems, leveraging renewable feedstocks to co-produce chemicals, energy, and materials within a single integrated facility [198]. When applied to FW, the biorefinery approach moves the waste hierarchy beyond simple recycling and recovery toward a circular bioeconomy model in which nutrient-rich stream is systematically valorized rather than disposed. A proposed framework in Figure 4 operationalizes this concept by coupling FW management with two complementary valorization routes that together close the mass and energy loss of the system.

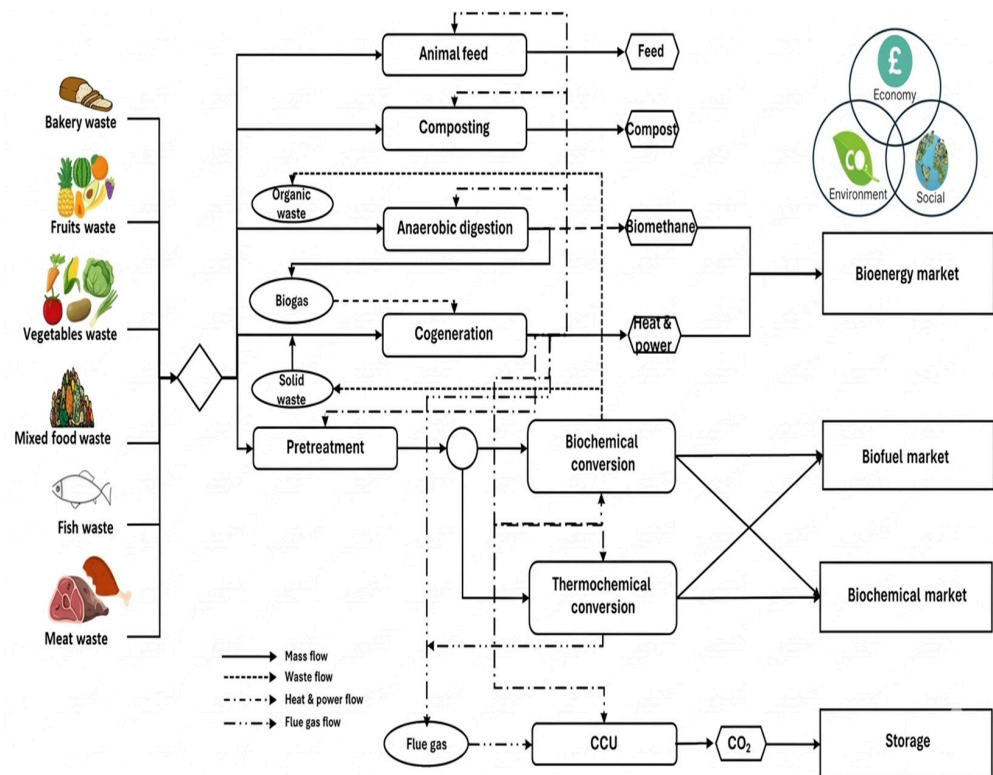


Figure 4. A proposed integrated FW management and valorization framework.

The framework depicted in Figure 4 illustrates the potential integration of FW management and valorization pathways within a circular system designed to maximize resource recovery from all incoming streams. Different categories of FW, including bakery, fruit, vegetable, mixed, fish, and meat waste, are first collected and pretreated before being distributed through a sorting node to either conventional FW management routes (animal feed, composting, AD, and incineration) or valorization pathways based on biochemical and thermochemical conversion. Importantly, the figure does not represent a fixed operational configuration; rather, it presents all feasible integration pathways that can later be assessed through optimization to determine the most suitable allocation of each stream. The integration strategy is established through cross-linkages between FW management and valorization processes, enabling residual streams generated in one pathway to be recovered and utilized in another. Organic residues from biochemical and thermochemical conversion can be redirected to AD as supplementary feedstock, while solid residues may be routed to incineration for energy recovery. Similarly, biogas from AD is not inherently assigned to a single use but may be directed to cogeneration depending on the optimal system configuration identified in subsequent analysis. In addition, flue gas produced from incineration can be integrated with a carbon capture unit (CCU), where the recovered CO₂ is either permanently stored or further utilized for the production of value-added products. Through these interconnected recovery loops, the framework demonstrates how FW management and valorization routes can operate as an integrated network that maximizes material, energy, and carbon recovery while minimizing final waste disposal, consistent with the principles of a circular bioeconomy.

The strategic integration of processes within such biorefineries enhances plant sustainability by improving energy efficiency, reducing water usage, recovering organic residues, and minimizing emissions. Several recent studies illustrate how these integration principles translate into measurable performance gains. Criado and Martín [199] exemplified circular economy principles in the fruit industry by designing an integrated biorefinery to produce

juice, limonene, high-value chemicals, energy, and fertilizer. Limonene was recovered from peel waste via steam explosion or hexane extraction, followed by AD to generate biogas, fertilizers, and utilities. Results showed that processing 1 kg of peel yielded 0.021 kg of limonene, 0.115 kg of biogas, 0.652 kg of dry fertilizer, and 8.8 GWh of electricity using a regenerative Rankine cycle. Pinch technology was employed to enhance energy efficiency, reduce operating costs, and optimize the overall process. Mailaram, et al. [200] assessed the techno-economic feasibility of producing lactic acid from 100 metric tons/day of BW under acid-neutral and low-pH fermentation scenarios. Integration between AD and co-generation was achieved by recovering unconverted organic residues from the lactic acid process and routing them to AD for biomethane production. The generated biomethane was subsequently utilized on-site for steam and heat generation, partially meeting the process energy demand while surplus energy was recovered as a co-product. Combined with pinch-based heat integration, these measures reduced utility costs by 15% and 11% for the acid-neutral and low-pH scenarios, respectively, decreasing LA production costs to \$2.07 kg⁻¹ and \$1.82 kg⁻¹, with minimum selling prices of \$3.52 kg⁻¹ and \$3.22 kg⁻¹. Hafyan, et al. [19] investigated a biorefinery co-producing bioethanol and SA from BW, assessing four process scenarios. Scenario 4, incorporating AD, combined heat and power (CHP), CC, and SA production, demonstrated superior performance, achieving a GWP of −0.344 kg CO₂-eq. Techno-economic analysis (TEA) confirmed its economic viability, with a 2.2-year PBP, 33% IRR, 32% return on investment (ROI), and a NPV of 163 M\$. In a subsequent study, Hafyan, et al. [201] developed a multi-objective optimization framework for integrated BW valorization that couples AD and incineration with biorefinery pathways. The model, a mixed-integer nonlinear programming problem solved via ϵ -constraint approach, simultaneously optimizes NPV, GWP savings, and employment generation under three heat supply strategies. Fully internal heat provision maximized environmental performance (361,741 tCO₂-eq/year GWP savings), while fully external heat delivered superior economic and social outcomes (NPV up to 733 M\$ and 4881 jobs).

7. Food Waste Management Challenges

Contamination is a major issue in managing FW. The fermentation process used in FW valorization is vulnerable to contamination when FW is mixed with other types of waste. To address this, a systematic distribution scheme for FW is needed to manage it separately from other waste. In particular, implementing a segregated FW collection system would help minimize the risk of contamination and ensure that FW can be effectively sourced for valorization, leading to a successful fermentation process and effective reuse of FW. However, collecting segregated FW from different supply chains can be challenging. Households, which generate the highest levels of FW, are not seen as a feasible source due to the complexity and cost of waste separation [202]. Therefore, surplus FW from retailers represents a more feasible source. In this context, take-back agreements (TBA), where bakeries manage the collection and treatment of unsold products, have been implemented in several European countries, enabling a controlled and less contaminated FW supply chain [203]. This approach creates a return system between bakeries and retailers, enabling a flow of uncontaminated BW and minimizing separation challenges.

Another challenge with using FW as feedstock is ensuring an uninterrupted supply. In practice, maintaining a steady supply of FW for valorization is difficult due to its seasonal production and its tendency to rot or decompose if stored for long periods. To ensure continuous operation, it is crucial to assess the process's flexibility in handling variations in feedstock composition. This assessment is essential because it directly impacts yield performance and product quality. To overcome this, it can be mitigated through two complementary strategies. First, supply chain bio-hubs can aggregate dispersed feed-

stock streams and apply preprocessing (e.g., pretreatment, process conversion) to improve stability, density, and storability, enabling year-round availability and more resilient logistics networks [204]. Second, feedstock blending allows multiple feedstock categories (e.g., FW, agricultural waste, industrial waste) to be co-processed, smoothing seasonal and compositional variability and ensuring continuous plant operation [205].

8. Decision-Making Approach of Food Waste Management Selection

This chapter discusses how optimization and decision-making approaches can be systematically constructed for the integration of FW management and valorization, with the aim of guiding the decision-maker toward the optimum system configuration. As depicted in Figure 5, the proposed approach comprises three sequential steps. Step 1—Identification. FW streams are categorized by type, composition, generation rate, and valorization potential, and mapped against the FW management hierarchy (prevention, recycling, recovery, disposal) and the available valorization pathways (biochemical and thermochemical conversion). Essential process data are collected at this stage, including conversion technologies, operating conditions, yields, and target products and substitutions. Step 2—Integration. Management strategies (animal feed, composting, AD, incineration) are combined with valorization pathways into a single biorefinery superstructure (Figure 4) that encodes all feasible recovery and conversion routes through internal mass, energy, and carbon loops. Step 3—Decision-making. The integrated system is evaluated against economic, environmental, and social objectives. MOO generates a Pareto frontier of non-dominated solutions across the three objectives, and MCDM methods normalize and weigh the conflicting criteria according to decision-maker preferences to identify the most sustainable compromise solution. Through this three-step approach, the integration of FW management and valorization becomes a transparent decision-support framework that defines the feasible integration space, navigates trade-offs across sustainability pillars, and converges on the optimum configuration that is technically feasible, economically viable, environmentally sound, and socially acceptable.

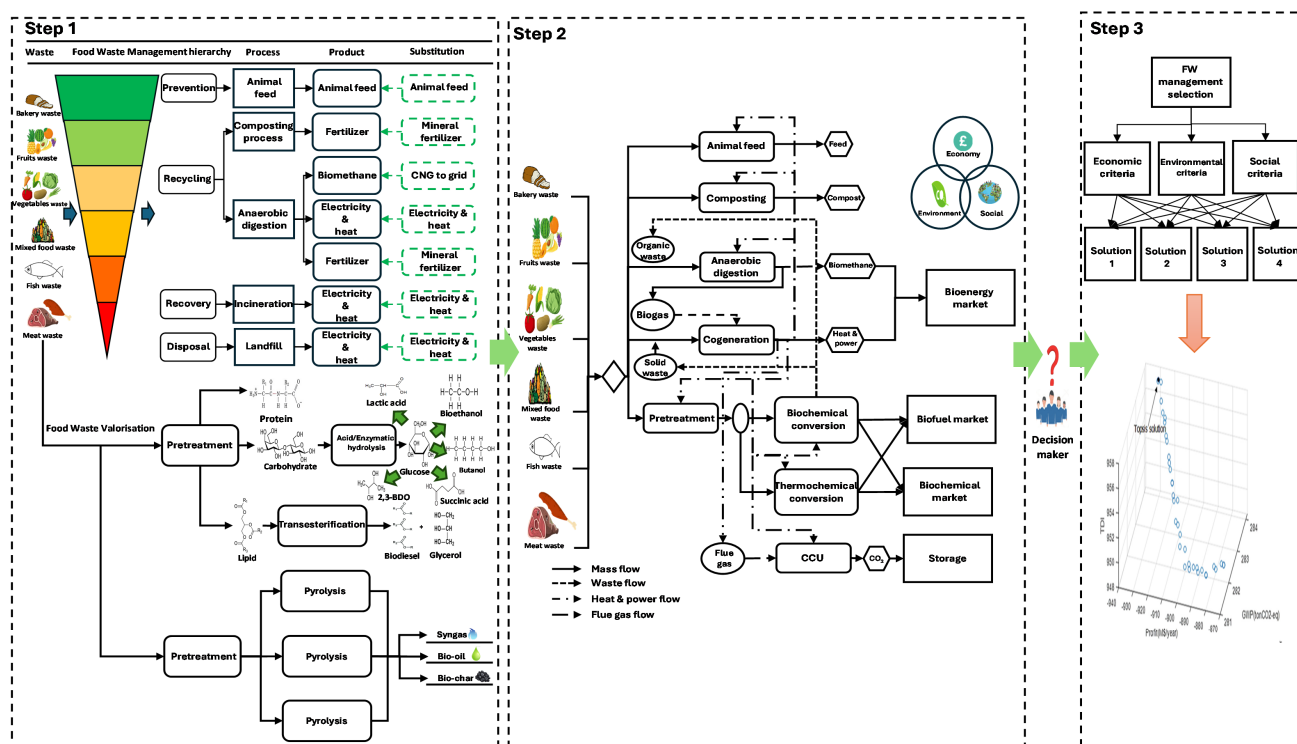


Figure 5. Decision making approach framework for integrated FW management selection.

8.1. Multi-Objective Optimization of Integrated Food Waste Management

8.1.1. General Formulation

MOO provides the mathematical foundation for identifying optimal configurations of integrated FW management and valorization systems. In its general form, MOO problem seeks to simultaneously optimize a vector of m conflicting objectives subject to a set of equality and inequality constraints, and is formulated as follows Equation (1):

$$\begin{aligned} \min_x F(x) &= [f_1(x), f_2(x), \dots, f_m(x)]^T \\ \text{s.t. } g_i(x) &\leq 0, \quad i = 1, \dots, p; \\ h_j(x) &= 0, \quad j = 1, \dots, q; \\ x &\in X \end{aligned} \quad (1)$$

where $F(x)$ is the vector of objective functions (economic, environmental, and social), $g_i(x)$ and $h_j(x)$ represent inequality and equality constraints (mass and energy balances, feedstock supply, capacity, policy, market demand, etc.), and x is the vector of decision variables (e.g., feedstock allocation, plant capacity, technology selection, operating conditions, etc.). Unlike single-objective problems, MOO does not yield a single optimal solution but a set of Pareto-optimal (non-dominated) solutions, in which any improvement in one objective necessarily degrades at least one other. This Pareto frontier represents the trade-off surface from which the decision-maker selects the preferred compromise solution. Applied to integrated FW management, the decision variables typically encode the allocation of each FW category (bakery, fruit, vegetable, mixed, fish, meat) across the available management routes (animal feed, composting, AD, incineration) and valorization pathways (biochemical and thermochemical conversion).

8.1.2. Problem Formulation Type

The mathematical formulation of MOO problem depends on the nature of the decision variables and whether the objective functions and constraints are linear or nonlinear [206]. This classification directly affects modelling capability, computational complexity, and solver selection for integrated FW systems. Four optimization classes are commonly used in FW management and biorefinery design. Linear programming (LP) employs continuous variables with linear equations and is mainly applied to simplified supply-chain problems such as FW allocation, transportation, and capacity distribution [207]. Nonlinear programming (NLP) retains continuous variables but incorporates nonlinear relationships, making it suitable for process-level optimization involving reaction kinetics, fermentation performance, energy balances, and heat integration [208]. Mixed-integer linear programming (MILP) extends LP by introducing binary or integer variables, enabling technology-selection and network-design decisions, for example, whether specific FW treatment routes, facilities, or processing units are installed, and is therefore widely used in superstructure and supply-chain optimization [209]. Mixed-integer nonlinear programming (MINLP) combines discrete technology-selection decisions with nonlinear process behavior and is the most comprehensive formulation for integrated FW management, particularly when both system configuration and operational performance must be optimized simultaneously [210].

8.1.3. Objective Functions in Integrated FW Optimization

The mathematical structure of an integrated FW superstructure optimization model is defined by two complementary elements: the objective functions that quantify the goals of the system, and the constraints that define the feasible region within which those objectives

can be pursued. Together they translate the qualitative concept of sustainability into a quantitative, optimizable formulation.

Objective functions in integrated biowaste MOO problems are constructed to reflect the three pillars of sustainability, economic, environmental, and social. The economic objective is evaluated through techno-economic analysis (TEA), with indicators such as NPV, IRR, PBP, return on investment (ROI), profit, total annualized cost (TAC), and operating cost; NPV is most commonly chosen as the maximization objective because it integrates capital, operating, and revenue streams over the plant lifetime in a single value [211]. The environmental objective is quantified through life cycle assessment (LCA) under ISO 14040/44 [212], with global warming potential (GWP, kg CO₂-eq) the most widely used indicator [213], and complementary metrics including cumulative energy demand, water footprint, acidification, eutrophication, and fossil resource depletion; for circular configurations, the avoided burden from displaced fossil products, are often preferred to highlight the integration benefit [201]. The social objective is defined according to the UNEP/SETAC guidelines, which align S-LCA with the ISO 14040 framework and structure social impact assessment across five main stakeholder categories and twenty-two associated sub-categories addressing labor rights, health and safety, fair wages, community engagement, and end-of-life responsibility [214].

8.1.4. Uncertainty Problem Optimization

Replacing a significant portion of fossil-based products with renewable feedstocks presents several challenges, particularly regarding ensuring a consistent supply. One of the main issues is the seasonal variability of renewable feedstocks, which creates supply inconsistencies for biorefineries [215]. Similarly, the integrated FW valorization pathway faces challenges due to the high variability of FW feedstock, leading to uncertainties in maintaining a stable supply throughout the year and over the operational lifetime of the plant [211]. To address these issues, the impact of fluctuations in FW feedstock type and composition is incorporated into the FW valorization superstructure. The general uncertainty-aware MOO formulation can be expressed as Equation (2):

$$\begin{aligned} \min_x \quad & \rho_{\xi}[F(x, \xi)] \\ \text{s.t.} \quad & \rho_{\xi}[g_i(x, \xi)] \leq 0, \quad i = 1, \dots, m \\ & h_j(x) = 0, \quad j = 1, \dots, p \end{aligned} \quad (2)$$

where x denotes the vector of decision variables, ξ represents the vector of uncertain parameters (feedstock supply, composition, market prices, etc.), F , g_i , h_i are the objective function, inequality constraint, and equality constraint respectively. $\rho_{\xi}[\cdot]$ is the expected-value operator under the probability distribution of ξ . Stochastic programming, robust optimization, and probabilistic modelling are the principal techniques used to operationalize this formulation. Table 4 summarizes data highlighting the optimization of bioenergy systems under uncertainty, primarily focusing on economic objectives, with some attention to environmental and social factors. A range of feedstocks, including agricultural residues, algae, woody biomass, MSW, and other waste materials, are utilized to produce bioethanol, biodiesel, electricity, and high-value biochemicals. The dominant modeling approach is MILP, with uncertainty managed through robust optimization (e.g., RP, DDRP, RPP) and stochastic techniques. Key uncertainties include biomass supply, product demand, and market prices. The findings indicate a trend toward integrated biorefineries, circular economy principles, and resilient bioenergy supply chains. However, the study also reveals a significant trade-off between profit and biomass quality variability. As highlighted by pre-

vious studies, uncertainty in feedstock quality emphasizes the importance of incorporating such considerations to ensure the reliability and efficiency of biorefinery processes.

The robustness aspect of uncertainty modeling is crucial for evaluating system performance under various uncertain conditions, ensuring that decisions remain effective even in worst-case scenarios [216]. Stochastic programming and robust optimization are commonly employed methods to address uncertainty in optimization models. Stochastic programming optimizes expected performance using probabilistic representations of uncertain parameters, making it suitable when reliable probabilistic data is available [217]. A key extension, two-stage stochastic programming, divides decision-making into two phases: initial strategic decisions, such as plant design, followed by operational adjustments once more information becomes available, enhancing flexibility in responding to uncertainties like feedstock supply and market prices [218,219]. However, stochastic approaches may underperform in rare but critical scenarios due to reliance on probabilistic data [220]. In contrast, robust optimization does not depend on probabilities but ensures feasibility under worst-case conditions by considering uncertainty within predefined bounds [221]. This method provides conservative solutions that prioritize reliability, making it ideal for environments where constraint satisfaction is critical [222,223]. Although less data-intensive and more tractable, robust optimization can result in overly cautious solutions that sacrifice optimal performance [224]. The choice between these methods depends on the availability of reliable data: stochastic optimization is preferred when such data is available, while robust optimization is more suitable when ensuring performance across all possible scenarios is paramount.

Table 4. Summary of the reviewed studies of the integration of biomass-based optimization.

Feedstock	Objective Function			Model Approach	Uncertain Parameters	Uncertainty Approach	Final Products	Reference
	Economic	Environmental	Social					
Beantalk, Rice straw, Hardwood and softwood	✓	-	-	MILP	Product demands	DDRP	Bioethanol & electricity	[223]
MSW	✓	✓	-	MILP	Demand & cost	2-stage SP	Electricity & biodiesel	[225]
Microalgae, wheat straw and corn stover	✓	-	-	MILP	Biomass supply, biofuel demand, price & costs	RP	Bioethanol	[221]
Beantalk, Rice straw, Hardwood and softwood	✓	-	-	MILP	Biomass supply	RP	Bioethanol, & electricity	[226]
Microalgae	✓	✓	-	-	Product demands	RP	Biodiesel, methanol, biochar & power	[227]
Woody biomass	✓	-	-	MILP	Biomass supply	DDRP	Power	[222]
Forest waste	✓	-	-	MILP	Biomass productivity and selling price of product	RP	Pulp, lignin, and power	[228]
Potato peel, sugarcane, willow, poplar, & cornstover	✓	✓	-	MINLP	Biomass feedstock and products	SP	Butadiene, Jet fuel, surfactant, lubricant, p-xylene, H ₂ & power	[229]
Rice straw, wheat straw, maize straw, cow manure, and hen	✓	✓	✓	MILP	Biomass feedstock, product demand, and cost	RP	Power & fertilizer	[230]
Algae	✓	✓	-	MINLP	Biomass supply	RPP	Biodiesel	[231]
Forest waste	✓	-	-	MILP	Biomass feedstock, product demand, and cost	RP	Syngas	[232]
Woody biomass and seaweed	✓	✓	-	MILP	Biomass feedstock and products	SP	Biofuel	[233]
Waste animal fat	✓	✓	-	MILP	Biomass supply and biodiesel demand	RPP	Biodiesel	[234]

Table 4. Cont.

Feedstock	Objective Function			Model Approach	Uncertain Parameters	Uncertainty Approach	Final Products	Reference
	Economic	Environmental	Social					
Sugarcane	-	✓	-	MILP	Biomass supply	RP	Bioethanol	[235]
Potato peels, poplar wood, red oak, sugarcane, corn stover	✓	✓	-	MINLP	Process conversion, market price of biomass & products	RP	PSA, electricity, butadiene, jet-fuel, surfactants, lubricants, and PX	[236]

DDRP: data driven robust programming; RP: robust programming; SP: Stochastic programming; RPP: robust probabilistic programming.

8.2. Multi-Criteria Decision Making of Integrated Food Waste Management

Developing decision-making systems is essential for effective FW disposal management. Investments should yield reasonable profits and align with environmental preferences, social acceptance, and long-term competitiveness. Sustainability assessment integrates scientific and policy research to meet stakeholder needs through a transdisciplinary approach. Due to the varied impacts of FW management on the environment, economy, and society, a robust assessment framework is crucial for making informed decisions and choosing sustainable practices [237]. Once the MOO step generates a Pareto frontier of non-dominated solutions across economic, environmental, and social objectives, a final compromise solution is required for implementation. MCDM provides this step by incorporating stakeholder preferences to rank Pareto-optimal alternatives [238]. As shown in Step 3 of Figure 5, the integrated FW management framework couples MOO and MCDM into a unified procedure, where MOO defines the trade-off surface and MCDM identifies the most preferred solution [239].

In general, an MCDM problem can be defined as selecting the most preferred alternative from a finite set of options $A = \{A_i \mid i = 1, 2, \dots, m\}$ evaluated using a set of criteria $C = \{C_j \mid j = 1, 2, \dots, n\}$ where the criteria may have different units and can represent conflicting objectives. A weight vector $W = \{w_j \mid j = 1, 2, \dots, n\}$ is assigned to reflect the relative importance of each criterion, with $\sum_{j=1}^n w_j = 1$. The performance of each alternative with respect to each criterion is represented in a decision matrix $M = [x_{ij}]$, where x_{ij} denotes the value of alternative A_i under criterion C_j . MCDM methods use this matrix and weight vector to score and rank alternatives, identifying either a single best solution or a subset of efficient (non-dominated) solutions. Conceptually, MCDM can be viewed as either selecting the most preferred alternative, grouping alternatives into preference classes, or identifying efficient non-dominated solutions where no improvement in one criterion is possible without sacrificing another [240].

Several MCDM methods are commonly applied in biorefinery decision-making. The Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) ranks alternatives by their relative geometric distance to an ideal and an anti-ideal solution, with the highest-ranked alternative selected as the compromise optimum. Zarei, et al. [241] applied this approach to a sustainable biofuel supply chain by generating the Pareto frontier between total annualized cost and GHG emissions using AUGMECON-R, then using TOPSIS to compute the closeness of each Pareto-optimal solution to the ideal and anti-ideal points. The compromise solution achieved a levelized cost of US\$6.63/gallon of gasoline-equivalent (GGE) and 674.83 g CO₂-eq/GGE. The Analytic Hierarchy Process (AHP) structures the decision problem hierarchically and derives weights from pairwise expert comparisons, making it well-suited to incorporating qualitative stakeholder input. Yadav, et al. [242] applied this approach to identify and rank sixteen obstacles hindering the implementation of lignocellulose biomass (LCB) gasification, decomposing the problem into a hierarchical framework based on the three AHP principles of decomposition, comparative evaluation,

and synthesis. The pairwise comparisons revealed that operational challenges were the most significant barrier (weight 0.1257), followed by gas cleaning (0.1107), consolidation of initial funds (0.1037), market establishment (0.0913), and harvesting and collection (0.0749). VIKOR identifies a compromise solution by ranking alternatives based on their closeness to the ideal point while balancing group utility against individual regret, making it particularly effective for problems with conflicting criteria. Nath, et al. [243] applied this approach to rank agricultural waste-based heterogeneous catalysts for biodiesel production, evaluating reported catalysts against five criteria: catalyst concentration (C1), methanol-to-oil ratio (C2), reaction temperature (C3), reaction time (C4), to be minimized and biodiesel yield (C5), to be maximized. The VIKOR ranking identified the plantain peel-derived catalyst as the top-performing alternative, followed by Musa paradisiaca peel and cocoa pod husk catalysts.

While individual MCDM methods are powerful, they often struggle to handle interdependence among criteria and uncertainty in expert judgement [244]. Hybrid MCDM approaches, which combine the complementary strengths of multiple techniques, have emerged as the most powerful class of methods for complex problems [245]. Wang, et al. [246] developed a framework using complex spherical fuzzy information to evaluate FW treatment methods, integrating mutual support and periodic decision information using complex spherical fuzzy information to capture the ambiguity and vagueness in expert opinions, a power-weighted average (PWA) operator to handle such uncertainties, and Additive Ratio Assessment (ARAS) Approach is used to help in determining the significance of different factors considered in the evaluation process. Rani, et al. [247] proposed a novel framework combining inter-criteria correlation (CRITIC) and multi-objective optimization (MULTIMORA) with single-valued neutrosophic sets (SVNSs) for assessing FW treatment methods. They applied the CRITIC technique to compute attribute weights and the MULTIMORA model to rank options, validating their approach through a case study and sensitivity analysis. In summary, both MCDM and MOO approaches play a critical role in enhancing decision-making for FW management by systematically incorporating economic, environmental, and social dimensions. MCDM methods are valuable for evaluating and ranking FW management alternatives based on stakeholder preferences, while MOO techniques enable the optimization of complex systems with multiple, often conflicting, objectives. When used together, these tools can support more informed and balanced decisions that align with sustainability goals and the principles of a circular bioeconomy. Strengthening the synergy between these approaches by embedding MCDM as a post-Pareto selection step within the MOO workflow, as proposed in this review, is therefore essential to advance sustainability-driven decision support for integrated FW management systems.

9. Conclusions

This work demonstrates that conventional FW management strategies, including animal feed production, composting, anaerobic digestion, incineration, and landfilling, can be significantly enhanced by integrating them with the biorefinery concept. Within this integrated framework, FW is no longer considered solely as a disposal challenge but is instead redefined as a valuable feedstock for the production of biofuels, biochemicals, and other high-value materials through both biochemical and thermochemical conversion pathways. This shift enables a transition from linear waste treatment systems to circular resource recovery systems.

A key insight from this study is that the overall sustainability of FW valorization is strongly dependent on the selection of end products. Products with high yields, strong market value, and favorable environmental performance, such as bioethanol, lactic acid, succinic acid, butanol, bio-oil, and biochar, are more suitable for large-scale implementation.

Therefore, process selection should not only focus on conversion efficiency but also on economic feasibility and environmental impact across the entire value chain.

To systematically address the complexity of FW-based biorefinery systems, mathematical multi-objective optimization has been employed to simultaneously evaluate economic performance, environmental sustainability, and social considerations under practical operational constraints. In addition, MCDM methods are integrated to rank alternative solutions and identify optimal pathways by incorporating the preferences of decision-makers, thereby bridging the gap between theoretical optimization and real-world implementation. Despite these advancements, FW valorization systems still face several challenges, including feedstock heterogeneity, contamination with other waste streams, seasonal variability, and inconsistencies in supply chain logistics. These issues directly affect process stability and scalability, highlighting the need for robust system design and adaptive optimization frameworks.

Future research should extend the proposed integrated optimization approach by incorporating a wider range of products, emerging conversion technologies, and full supply chain modelling from cradle to grave. In particular, coupling upstream collection systems with downstream biorefinery operations would enable a more comprehensive assessment of system performance. Such developments would support the design of fully integrated circular bioeconomy systems that maximize resource recovery, minimize environmental burden, and enhance economic viability. Therefore, the study provides a systematic framework for integrating FW management with biorefinery-based valorization, supported by optimization and decision-making tools, thereby contributing to the development of sustainable, scalable, and circular solutions for global FW challenges.

Author Contributions: R.H.H.: Conceptualization, Methodology, Investigation, Data Curation, Formal analysis, Writing—original draft, Writing—review & editing; V.K.: Writing—review & editing; S.K.M.: Writing—review & editing; J.S.: Writing—original draft, Writing—review & editing; S.G.: Supervision, Conceptualization, Methodology, Investigation, Data Curation, Formal analysis, Writing—original draft, Writing—review & editing. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

FW	Food waste
FAO	Food and Agricultural Organization
UNEP	United Nations Environmental Programme
LCA	Life cycle assessment
USDA	United States Department of Agriculture
EPA	Environmental Protection Agency
NEA	National Environmental Agency
AVA	AgriFood and Veterinary Authority
AD	Anaerobic digestion
WWTPs	Wastewater treatment plant sludge
VOCs	Volatile organic compound

LFG	Landfill gas
DOE	Department of Energy
MOO	multi-objective optimization
MCDM	multi-criteria decision-making
TEA	Techno-economic assessment
SIA	Social impact assessment
CAPEX	Capital expenditure
OPEX	Operational expenditure
MILP	Mixed-integer linear programming
MINLP	Mixed-integer nonlinear programming
DDRP	Data driven robust programming
RP	Robust programming
SP	Stochastic programming
RPP	Robust probabilistic programming
AHP	Analytic hierarchy process
PWA	Power-weighted average
ARAS	Additive ratio assessment
CRITIC	Combining inter-criteria correlation
SVNSs	Single-valued neutrosophic sets

References

- Burke, D.T.; Hynds, P.; Priyadarshini, A. Quantifying farm-to-fork greenhouse gas emissions for five dietary patterns across Europe and North America: A pooled analysis from 2009 to 2020. *Resour. Environ. Sustain.* **2023**, *12*, 100108. [CrossRef]
- Gonçalves, J.; Anjos, O.; Guiné, R.P.F. A Revisit of Plant Food Waste Along Food Supply Chains: Impacts and Perspectives. *Foods* **2025**, *14*, 1364. [CrossRef]
- UNEP. Food Waste Index Report 2024. Think Eat Save: Tracking Progress to Halve Global Food Waste. 2024. Available online: <https://wedocs.unep.org/20.500.11822/45230> (accessed on 12 January 2025).
- Caldeira, C.; Vlysidis, A.; Fiore, G.; De Laurentiis, V.; Vignali, G.; Sala, S. Sustainability of food waste biorefinery: A review on valorisation pathways, techno-economic constraints, and environmental assessment. *Bioresour. Technol.* **2020**, *312*, 123575. [CrossRef]
- Kumar, A.; Ramamoorthy, D.; Kumar, N.; Chandra, P. Chapter 13—Food waste conversion into value-added products: Different pathways, current challenges, and opportunities. In *Bio-Based Materials and Waste for Energy Generation and Resource Management*; Hussain, C.M., Kushwaha, A., Bharagava, R.N., Goswami, L., Eds.; Elsevier: Amsterdam, The Netherlands, 2023; Volume 5, pp. 387–409.
- Rana, M.S.; Bhushan, S.; Prajapati, S.K.; Preethi, Kavitha, S. Chapter 15—Techno-economic analysis and environmental aspects of food waste management. In *Food Waste to Valuable Resources*; Banu, J.R., Kumar, G., Gunasekaran, M., Kavitha, S., Eds.; Academic Press: Cambridge, MA, USA, 2020; pp. 325–342. [CrossRef]
- Bräutigam, K.-R.; Jörisen, J.; Priefer, C. The extent of food waste generation across EU-27: Different calculation methods and the reliability of their results. *Waste Manag. Res.* **2014**, *32*, 683–694. [CrossRef]
- WRAP. UK Food Waste & Food Surplus—Key Facts. In *Food Surplus and Waste in the UK—Key Facts*; WRAP: Banbury, UK, 2025. Available online: <https://www.wrap.ngo/resources/report/uk-food-waste-food-surplus-key-facts> (accessed on 10 July 2025).
- Hu, P.; Toma, L.T.; Alam, A.; Ahmmed, M.T.; Islam, M.J.; Farhana, K.; Sultana, M.; Bhuiyan, M.A. A comprehensive review of food waste management in attaining SDG 12.3 goals: Insights from Asian countries. *Front. Sustain. Food Syst.* **2026**, *9*, 1710361. [CrossRef]
- European Commission: Directorate-General for Research and Innovation, E4tech, BTG, ICONS, FNR and WUR. *EU Biorefinery Outlook to 2030—Studies on Support to Research and Innovation Policy in the Area of Bio-Based Products and Services*; Publications Office of the European Union: Luxembourg, 2021. Available online: <https://data.europa.eu/doi/10.2777/103465> (accessed on 10 May 2026).
- Department for Environment; Food and Rural Affairs (Defra). Our Waste, Our Resources: A Strategy for England. 2018. Available online: <https://www.gov.uk/government/publications/resources-and-waste-strategy-for-england> (accessed on 31 January 2024).
- DEFRA. Department of Energy. In *Climate Change (DECC) and Department for Environment, Food & Rural Affairs. Anaerobic Digestion Strategy and Action Plan*; DEFRA: London, UK, 2011. Available online: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/69400/anaerobic-digestion-strat-action-plan.pdf (accessed on 31 January 2024).
- Liu, K.-M.; Lin, S.-H.; Hsieh, J.-C.; Tzeng, G.-H. Improving the food waste composting facilities site selection for sustainable development using a hybrid modified MADM model. *Waste Manag.* **2018**, *75*, 44–59. [CrossRef] [PubMed]

14. Bakkaloglu, S.; Cooper, J.; Hawkes, A. Life cycle environmental impact assessment of methane emissions from the biowaste management strategy of the United Kingdom: Towards net zero emissions. *J. Clean. Prod.* **2022**, *376*, 134229. [CrossRef]
15. Otles, S.; Kartal, C. 11—Food Waste Valorization. In *Sustainable Food Systems from Agriculture to Industry*; Galanakis, C.M., Ed.; Academic Press: Cambridge, MA, USA, 2018; pp. 371–399. [CrossRef]
16. Talan, A.; Tiwari, B.; Yadav, B.; Tyagi, R.D.; Wong, J.W.C.; Drogui, P. Food waste valorization: Energy production using novel integrated systems. *Bioresour. Technol.* **2021**, *322*, 124538. [CrossRef] [PubMed]
17. Sadhukhan, J.; Dugmore, T.I.J.; Matharu, A.; Martinez-Hernandez, E.; Aburto, J.; Rahman, P.K.S.M.; Lynch, J. Perspectives on “Game Changer” Global Challenges for Sustainable 21st Century: Plant-Based Diet, Unavoidable Food Waste Biorefining, and Circular Economy. *Sustainability* **2020**, *12*, 1976. [CrossRef]
18. Ankush; Khushboo; Dubey, K.K. 17—Food industry waste biorefineries: Future energy, valuable recovery, and waste treatment. In *Refining Biomass Residues for Sustainable Energy and Bioproducts*; Kumar, R.P., Gnansounou, E., Raman, J.K., Baskar, G., Eds.; Academic Press: Cambridge, MA, USA, 2020; pp. 391–406. [CrossRef]
19. Hafyan, R.H.; Mohanarajan, J.; Uppal, M.; Kumar, V.; Narisetty, V.; Maity, S.K.; Sadhukhan, J.; Gadkari, S. Integrated biorefinery for bioethanol and succinic acid co-production from bread waste: Techno-economic feasibility and life cycle assessment. *Energy Convers. Manag.* **2024**, *301*, 118033. [CrossRef]
20. Rajendran, N.; Han, J. Techno-economic analysis and life cycle assessment of poly (butylene succinate) production using food waste. *Waste Manag.* **2023**, *156*, 168–176. [CrossRef]
21. Li, Y.; Rosenthal, A.; Zhang, J.; Hawkins, T.R.; Liang, Y.; Urgan-Demirtas, M.; Bian, Y.; Ren, Z.J.; Tuteja, A.; Speer, D. Technoeconomic and Life Cycle Analysis of an Integrated Fermentation and Microbial Electrochemical Process for Volatile Fatty Acid Production from Food Waste. *ACS Sustain. Chem. Eng.* **2026**, *14*, 8660–8669. [CrossRef]
22. Santagata, R.; Ripa, M.; Genovese, A.; Ulgiati, S. Food waste recovery pathways: Challenges and opportunities for an emerging bio-based circular economy. A systematic review and an assessment. *J. Clean. Prod.* **2021**, *286*, 125490. [CrossRef]
23. Lenka, B.; El Fels, L.; Acharya, R.; Raklami, A. Harnessing the untapped value of food waste: A review of integrated valorization technologies. *J. Mater. Cycles Waste Manag.* **2026**, *28*, 57–78. [CrossRef]
24. Arvelli, S.; Jia, L.; Zhang, M.; Zhao, J. Review of Advanced Technologies and Circular Pathways for Food Waste Valorization. *J. Agric. Food Chem.* **2025**, *73*, 16085–16108. [CrossRef]
25. Hafyan, R.H.; Mohanarajan, J.; Uppal, M.; Kumar, V.; Narisetty, V.; Maity, S.K.; Sadhukhan, J.; Gadkari, S. Bread waste valorization: A review of sustainability aspects and challenges. *Front. Sustain. Food Syst.* **2024**, *8*, 1334801. (In English) [CrossRef]
26. Malik, B.X.; Smith, L.; Stewart, I.; Burnett, N. Food Waste in the UK. Available online: <https://commonslibrary.parliament.uk/research-briefings/cbp-7552/> (accessed on 12 April 2024).
27. Murphy, F. *Food Loss and Waste: Quantification, Impacts and Potential for Sustainable Management*; Task 36; IEA Bioenergy: Paris, France, 2024.
28. WRAP. Food Surplus and Waste in the UK Key Facts—Updated November 2023. 2023. Available online: <https://wrap.org.uk/resources/report/food-surplus-and-waste-uk-key-facts-updated-november-2023> (accessed on 31 January 2024).
29. Todd, E.C.D.; Faour-Klingbeil, D. Impact of Food Waste on Society, Specifically at Retail and Foodservice Levels in Developed and Developing Countries. *Foods* **2024**, *13*, 2098. [CrossRef] [PubMed]
30. Mohamed Yusoff, N.I.B.; Godsell, J.; Woolley, E. Towards zero waste: A comprehensive framework for categorizing household food waste. *Sustain. Prod. Consum.* **2024**, *48*, 1–13. [CrossRef]
31. Abdelradi, F. Food waste behaviour at the household level: A conceptual framework. *Waste Manag.* **2018**, *71*, 485–493. [CrossRef] [PubMed]
32. Elgarahy, A.M.; Eloffy, M.G.; Alengebawy, A.; El-Sherif, D.M.; Gaballah, M.S.; Elwakeel, K.Z.; El-Qelish, M. Sustainable management of food waste; pre-treatment strategies, techno-economic assessment, bibliometric analysis, and potential utilizations: A systematic review. *Environ. Res.* **2023**, *225*, 115558. [CrossRef]
33. Banks, C.; Heaven, S.; Zhang, Y.; Baier, U. Food Waste Digestion: Anaerobic Digestion of Food Waste for a Circular Economy. 2018. Available online: <https://www.ieabioenergy.com/blog/publications/food-waste-digestion-anaerobic-digestion-of-food-waste-for-a-circular-economy/> (accessed on 10 July 2025).
34. Yang, Y.-F.; Ye, G.-B.; Wang, H.-J.; Li, H.-Y.; Lin, C.S.K.; Zheng, X.-F.; Pugazhendhi, A.; Wang, X. Utilization of lipidic food waste as low-cost nutrients for enhancing the potentiality of biofuel production from engineered diatom under temperature variations. *Bioresour. Technol.* **2023**, *387*, 129611. [CrossRef]
35. Priefer, C.; Jörissen, J.; Braeutigam, K.-R. *Options for Cutting Down on Food Waste—Layman’s Summary*; STOA: Brussels, Belgium, 2013. Available online: [https://www.europarl.europa.eu/stoa/en/document/IPOL-JOIN_ET\(2013\)513515/](https://www.europarl.europa.eu/stoa/en/document/IPOL-JOIN_ET(2013)513515/) (accessed on 10 July 2025).
36. Salimi, E.; Saragas, K.; Taheri, M.E.; Novakovic, J.; Barampouti, E.M.; Mai, S.; Moustakas, K.; Malamis, D.; Loizidou, M. The Role of Enzyme Loading on Starch and Cellulose Hydrolysis of Food Waste. *Waste Biomass Valorization* **2019**, *10*, 3753–3762. [CrossRef]

37. Kumar, V.; Longhurst, P. Recycling of food waste into chemical building blocks. *Curr. Opin. Green Sustain. Chem.* **2018**, *13*, 118–122. [\[CrossRef\]](#)
38. Yukesh Kannah, R.; Merrylin, J.; Poornima Devi, T.; Kavitha, S.; Sivashanmugam, P.; Kumar, G.; Rajesh Banu, J. Food waste valorization: Biofuels and value added product recovery. *Bioresour. Technol. Rep.* **2020**, *11*, 100524. [\[CrossRef\]](#)
39. Wang, L.; Shen, F.; Yuan, H.; Zou, D.; Liu, Y.; Zhu, B.; Li, X. Anaerobic co-digestion of kitchen waste and fruit/vegetable waste: Lab-scale and pilot-scale studies. *Waste Manag.* **2014**, *34*, 2627–2633. [\[CrossRef\]](#)
40. Vavouraki, A.I.; Volioti, V.; Kornaros, M.E. Optimization of thermo-chemical pretreatment and enzymatic hydrolysis of kitchen wastes. *Waste Manag.* **2014**, *34*, 167–173. [\[CrossRef\]](#)
41. Bhatt, A.H.; Tao, L. Economic Perspectives of Biogas Production via Anaerobic Digestion. *Bioengineering* **2020**, *7*, 74. [\[CrossRef\]](#)
42. Browne, J.D.; Murphy, J.D. The impact of increasing organic loading in two phase digestion of food waste. *Renew. Energy* **2014**, *71*, 69–76. [\[CrossRef\]](#)
43. Zhang, J.; Gu, D.; Chen, J.; He, Y.; Dai, Y.; Loh, K.-C.; Tong, Y.W. Assessment and optimization of a decentralized food-waste-to-energy system with anaerobic digestion and CHP for energy utilization. *Energy Convers. Manag.* **2021**, *228*, 113654. [\[CrossRef\]](#)
44. Hafid, H.S.; Nor'Aini, A.R.; Mokhtar, M.N.; Talib, A.T.; Baharuddin, A.S.; Umi Kalsom, M.S. Over production of fermentable sugar for bioethanol production from carbohydrate-rich Malaysian food waste via sequential acid-enzymatic hydrolysis pretreatment. *Waste Manag.* **2017**, *67*, 95–105. [\[CrossRef\]](#)
45. Shen, F.; Yuan, H.; Pang, Y.; Chen, S.; Zhu, B.; Zou, D.; Liu, Y.; Ma, J.; Yu, L.; Li, X. Performances of anaerobic co-digestion of fruit & vegetable waste (FVW) and food waste (FW): Single-phase vs. two-phase. *Bioresour. Technol.* **2013**, *144*, 80–85. [\[CrossRef\]](#)
46. Pedreschi, F.; Cocio, C.; Moyano, P.; Troncoso, E. Oil distribution in potato slices during frying. *J. Food Eng.* **2008**, *87*, 200–212. [\[CrossRef\]](#)
47. Gontariu, I.; Buculei, A. The appreciation and determination the chemical composition of the tubercles at some potato grades. *J. Agroaliment. Process. Technol.* **2010**, *16*, 54–58.
48. Damto, T.; Chala, G. Effect of blanching and frying time on the sensory quality of fried sweet potato chips. *Food Nutr. Sci. Int. J.* **2019**, *3*, 1–17.
49. Robertson, T.M.; Alzaabi, A.Z.; Robertson, M.D.; Fielding, B.A. Starchy Carbohydrates in a Healthy Diet: The Role of the Humble Potato. *Nutrients* **2018**, *10*, 1764. [\[CrossRef\]](#)
50. Senanayake, S.; Gunaratne, A.; Ranaweera, K.; Bamunuarachchi, A. Physico-chemical properties of five cultivars of sweet potato (*Ipomea batatas* Lam (L)) root tubers grown in Sri Lanka. *Trop. Agric.* **2013**, *90*, 87–96.
51. Narisetty, V.; Nagarajan, S.; Gadkari, S.; Ranade, V.V.; Zhang, J.; Patchigolla, K.; Bhatnagar, A.; Kumar Awasthi, M.; Pandey, A.; Kumar, V. Process optimization for recycling of bread waste into bioethanol and biomethane: A circular economy approach. *Energy Convers. Manag.* **2022**, *266*, 115784. [\[CrossRef\]](#)
52. Leung, C.C.J.; Cheung, A.S.Y.; Zhang, A.Y.-Z.; Lam, K.F.; Lin, C.S.K. Utilisation of waste bread for fermentative succinic acid production. *Biochem. Eng. J.* **2012**, *65*, 10–15. [\[CrossRef\]](#)
53. Adessi, A.; Venturi, M.; Candelieri, F.; Galli, V.; Granchi, L.; De Philippis, R. Bread wastes to energy: Sequential lactic and photo-fermentation for hydrogen production. *Int. J. Hydrogen Energy* **2018**, *43*, 9569–9576. [\[CrossRef\]](#)
54. Han, W.; Huang, J.; Zhao, H.; Li, Y. Continuous biohydrogen production from waste bread by anaerobic sludge. *Bioresour. Technol.* **2016**, *212*, 1–5. [\[CrossRef\]](#)
55. Haque, M.A.; Kachrimanidou, V.; Koutinas, A.; Lin, C.S.K. Valorization of bakery waste for biocolorant and enzyme production by *Monascus purpureus*. *J. Biotechnol.* **2016**, *231*, 55–64. [\[CrossRef\]](#)
56. Gómez-Maqueo, A.; Escobedo-Avellaneda, Z.; Welti-Chanes, J. Phenolic Compounds in Mesoamerican Fruits—Characterization, Health Potential and Processing with Innovative Technologies. *Int. J. Mol. Sci.* **2020**, *21*, 18357. [\[CrossRef\]](#)
57. Maldonado-Celis, M.E.; Yahia, E.M.; Bedoya, R.; Landázuri, P.; Loango, N.; Aguillón, J.; Restrepo, B.; Guerrero Ospina, J.C. Chemical Composition of Mango (*Mangifera indica* L.) Fruit: Nutritional and Phytochemical Compounds. *Front. Plant Sci.* **2019**, *10*, 1073. (In English) [\[CrossRef\]](#)
58. Dhumal, S.; Karale, A.; Garande, V.; Chavan, U.; Jadhav, S.; Kad, V. Recent advances and developments in pomegranate processing and utilization: A review. *J. Agric. Crop Sci.* **2012**, *1*, 1–17.
59. De Matos, M.E.; Bianchi Pedroni Medeiros, A.; De Melo Pereira, G.V.; Thomaz Soccol, V.; Soccol, C.R. Production and Characterization of a Distilled Alcoholic Beverage Obtained by Fermentation of Banana Waste (*Musa cavendishii*) from Selected Yeast. *Fermentation* **2017**, *3*, 62. [\[CrossRef\]](#)
60. Seal, T.; Pillai, B.; Chaudhuri, K. Nutritional potential of wild edible fruits, traditionally used by the local people of Meghalaya state in India. *Indian J. Nat. Prod. Resour. (IJNPR) [Former. Nat. Prod. Radiance (NPR)]* **2015**, *5*, 359–364.
61. Ebabhi, A.; Adebayo, R. Nutritional values of vegetables. In *Vegetable Crops-Health Benefits and Cultivation*; IntechOpen: London, UK, 2022. [\[CrossRef\]](#)

62. Houn gla, E.J.H.; Gbankoto, A.; Miz ehoun-Adissoda, C.; Anani, C.B.L.; E dorh, P.A.; Moutaïrou, K.; Sohoun hloué, D.C. Nutrient Composition and Heavy Metals Content of Three Leafy Vegetables (*Amaranthus cruentus* L., *Lactuca sativa* L., *Solanum macrocarpon* L.) in Porto-Novo, Republic of Benin. *J. Food Nutr. Res.* **2020**, *8*, 80–86.
63. Das, N.; Khuntia, B.; Raychaudhuri, U.; Dora, K.; Ganguly, S. Effect of water washing on the functional properties of fish meat. *Int. J. Med. Microbiol. Trop. Dis.* **2015**, *1*, 8–12.
64. Ajeeshkumar, K.; Vishnu, K.; Kumari, K.R.; Navaneethan, R.; Asha, K.; Ganesan, B.; Niladri, S.; Anandan, R.; Mathew, S. Biochemical composition and heavy metal content of selected marine fish from the Gulf of Mannar, India. *J. Fish. Technol.* **2015**, *52*, 164–169.
65. Lilly, T.; Immaculate, J.; Jamila, P. Macro and micronutrients of selected marine fishes in Tuticorin, South East coast of India. *Int. Food Res. J.* **2017**, *24*, 191–201.
66. Hammad, H.; Ma, M.; Damaka, A.; Elkhedir, A.; Jin, G. Effect of freeze and re-freeze on chemical composition of beef and poultry meat at storage period 4.5 months (SP4. 5). *J. Food Process. Technol.* **2019**, *10*, 5.
67. Choe, J.-H.; Yang, H.-S.; Lee, S.-H.; Go, G.-W. Characteristics of pork belly consumption in South Korea and their health implication. *J. Anim. Sci. Technol.* **2015**, *57*, 22. [\[CrossRef\]](#)
68. Murphy, K.J.; Thomson, R.L.; Coates, A.M.; Buckley, J.D.; Howe, P.R.C. Effects of Eating Fresh Lean Pork on Cardiometabolic Health Parameters. *Nutrients* **2012**, *4*, 711–723. [\[CrossRef\]](#)
69. Chen, C.R.; Chen, R.J.C. Using Two Government Food Waste Recognition Programs to Understand Current Reducing Food Loss and Waste Activities in the U.S. *Sustainability* **2018**, *10*, 2760. [\[CrossRef\]](#)
70. Blanchard, C.; Harris, P.; Pocock, C.; McCabe, B.K. Food and Garden Organic Waste Management in Australia: Co-Benefits for Regional Communities and Local Government. *Sustainability* **2023**, *15*, 9901. [\[CrossRef\]](#)
71. Joshi, P.; Visvanathan, C. Sustainable management practices of food waste in Asia: Technological and policy drivers. *J. Environ. Manag.* **2019**, *247*, 538–550. [\[CrossRef\]](#)
72. Jia, B.; Ng, B.; Mao, Y.; Chen, C.-L.; Rajagopal, R.; Wang, J.-Y. Municipal food waste management in Singapore: Practices, challenges and recommendations. *J. Mater. Cycles Waste Manag.* **2015**, *19*, 560–569. [\[CrossRef\]](#)
73. Lee, E.; Shurson, G.; Oh, S.-H.; Jang, J.-C. The Management of Food Waste Recycling for a Sustainable Future: A Case Study on South Korea. *Sustainability* **2024**, *16*, 854. [\[CrossRef\]](#)
74. Meng, M.; Wen, Z.; Luo, W.; Wang, S. Approaches and Policies to Promote Zero-Waste City Construction: China's Practices and Lessons. *Sustainability* **2021**, *13*, 13537. [\[CrossRef\]](#)
75. EC. Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008 on Waste and Repealing Certain Directives (Text with EEA Relevance). 2008. Available online: <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32008L0098> (accessed on 10 July 2025).
76. Facchini, F.; Silvestri, B.; Digiesi, S.; Lucchese, A. Agri-food loss and waste management: Win-win strategies for edible discarded fruits and vegetables sustainable reuse. *Innov. Food Sci. Emerg. Technol.* **2023**, *83*, 103235. [\[CrossRef\]](#)
77. Brancoli, P.; Bolton, K.; Eriksson, M. Environmental impacts of waste management and valorisation pathways for surplus bread in Sweden. *Waste Manag.* **2020**, *117*, 136–145. [\[CrossRef\]](#)
78. Eriksson, M.; Strid, I.; Hansson, P.-A. Carbon footprint of food waste management options in the waste hierarchy—A Swedish case study. *J. Clean. Prod.* **2015**, *93*, 115–125. [\[CrossRef\]](#)
79. San Martín, D.; Ramos, S.; Zufía, J. Valorisation of food waste to produce new raw materials for animal feed. *Food Chem.* **2016**, *198*, 68–74. [\[CrossRef\]](#)
80. Quintero-Herrera, S.; Zwolinski, P.; Evrard, D.; Cano-Gómez, J.J.; Rivas-García, P. Turning food loss and waste into animal feed: A Mexican spatial inventory of potential generation of agro-industrial wastes for livestock feed. *Sustain. Prod. Consum.* **2023**, *41*, 36–48. [\[CrossRef\]](#)
81. Boumans, I.J.M.M.; Schop, M.; Bracke, M.B.M.; de Boer, I.J.M.; Gerrits, W.J.J.; Bokkers, E.A.M. Feeding food losses and waste to pigs and poultry: Implications for feed quality and production. *J. Clean. Prod.* **2022**, *378*, 134623. [\[CrossRef\]](#)
82. Wong, M.-H.; Mo, W.-Y.; Choi, W.-M.; Cheng, Z.; Man, Y.-B. Recycle food wastes into high quality fish feeds for safe and quality fish production. *Environ. Pollut.* **2016**, *219*, 631–638. [\[CrossRef\]](#)
83. Siddiqui, Z.; Hagare, D.; Jayasena, V.; Swick, R.; Rahman, M.M.; Boyle, N.; Ghodrati, M. Recycling of food waste to produce chicken feed and liquid fertiliser. *Waste Manag.* **2021**, *131*, 386–393. [\[CrossRef\]](#)
84. Tian, H.; Wang, X.; Lim, E.Y.; Lee, J.T.E.; Ee, A.W.L.; Zhang, J.; Tong, Y.W. Life cycle assessment of food waste to energy and resources: Centralized and decentralized anaerobic digestion with different downstream biogas utilization. *Renew. Sustain. Energy Rev.* **2021**, *150*, 111489. [\[CrossRef\]](#)
85. Sardarmehni, M.; Levis, J.W.; Barlaz, M.A. What Is the Best End Use for Compost Derived from the Organic Fraction of Municipal Solid Waste? *Environ. Sci. Technol.* **2021**, *55*, 73–81. [\[CrossRef\]](#)
86. Amato, A.; Tsigkou, K.; Becci, A.; Beolchini, F.; Ippolito, N.M.; Ferella, F. Life Cycle Assessment of Biomethane vs. Fossil Methane Production and Supply. *Energies* **2023**, *16*, 4555. [\[CrossRef\]](#)

87. Karthikeyan, O.P.; Mehariya, S.; Chung Wong, J.W. Bio-refining of food waste for fuel and value products. *Energy Procedia* **2017**, *136*, 14–21. [\[CrossRef\]](#)
88. Yan, J.; Salman, C.A. Chapter 2—Waste-to-energy (WtE): Current technologies and their future potential. In *Waste Biorefineries*; Yan, J., Salman, C.A., Eds.; Elsevier: Amsterdam, The Netherlands, 2023; pp. 25–61. [\[CrossRef\]](#)
89. Ouadi, M.; Bashir, M.A.; Speranza, L.G.; Jahangiri, H.; Hornung, A. Food and Market Waste—A Pathway to Sustainable Fuels and Waste Valorization. *Energy Fuels* **2019**, *33*, 9843–9850. [\[CrossRef\]](#)
90. Kaur, A.; Bharti, R.; Sharma, R. Municipal solid waste as a source of energy. *Mater. Today Proc.* **2023**, *81*, 904–915. [\[CrossRef\]](#)
91. Hla, S.S.; Roberts, D. Characterisation of chemical composition and energy content of green waste and municipal solid waste from Greater Brisbane, Australia. *Waste Manag.* **2015**, *41*, 12–19. [\[CrossRef\]](#)
92. Đurđević, D.; Blecich, P.; Jurić, Ž. Energy Recovery from Sewage Sludge: The Case Study of Croatia. *Energies* **2019**, *12*, 1927. [\[CrossRef\]](#)
93. Xiao, H.; Cheng, Q.; Liu, M.; Li, L.; Ru, Y.; Yan, D. Industrial disposal processes for treatment of polychlorinated dibenzo-p-dioxins and dibenzofurans in municipal solid waste incineration fly ash. *Chemosphere* **2020**, *243*, 125351. [\[CrossRef\]](#)
94. Delkash, M. Air Emissions from Combustion and Incineration Processes: Insights into Air Quality and US EPA Regulations. *Water Air Soil Pollut.* **2025**, *237*, 104. [\[CrossRef\]](#)
95. Sarkar, N.; Ganguly, A.; Chatterjee, P.K. 8—Valorization of food waste. In *Handbook of Advanced Approaches Towards Pollution Prevention and Control*; Rahman, R.O.A., Hussain, C.M., Eds.; Elsevier: Amsterdam, The Netherlands, 2021; pp. 157–172. [\[CrossRef\]](#)
96. El-Saadony, M.T.; Saad, A.M.; Fahmy, M.A.; Mohammed, D.M.; Salem, H.M.; Abd El-Mageed, T.A.; Abu-Elsaoud, A.M.; Alsyad, K.M.; Ahmed, A.E.; Al-Najjar, M.A.A.; et al. Hazardous landfill leachate: Integrated treatment strategies, regulatory frameworks, and circular economy perspectives. *Ecotoxicol. Environ. Saf.* **2026**, *312*, 119878. [\[CrossRef\]](#)
97. Bouyakhssass, R.; Souabi, S.; Bouaouda, S.; Taleb, A.; Kurniawan, T.A.; Liang, X.; Goh, H.H.; Anouzla, A. Adding value to unused landfill gas for renewable energy on-site at Oum Azza landfill (Morocco): Environmental feasibility and cost-effectiveness. *Trends Food Sci. Technol.* **2023**, *142*, 104168. [\[CrossRef\]](#)
98. Vandermeersch, T.; Alvarenga, R.A.F.; Ragaert, P.; Dewulf, J. Environmental sustainability assessment of food waste valorization options. *Resour. Conserv. Recycl.* **2014**, *87*, 57–64. [\[CrossRef\]](#)
99. Alsaleh, A.; Aleisa, E. Triple Bottom-Line Evaluation of the Production of Animal Feed from Food Waste: A Life Cycle Assessment. *Waste Biomass Valorization* **2023**, *14*, 1169–1195. [\[CrossRef\]](#)
100. Evangelisti, S.; Lettieri, P.; Borello, D.; Clift, R. Life cycle assessment of energy from waste via anaerobic digestion: A UK case study. *Waste Manag.* **2014**, *34*, 226–237. [\[CrossRef\]](#)
101. Slorach, P.C.; Jeswani, H.K.; Cuéllar-Franca, R.; Azapagic, A. Environmental sustainability of anaerobic digestion of household food waste. *J. Environ. Manag.* **2019**, *236*, 798–814. [\[CrossRef\]](#)
102. Slorach, P.C.; Jeswani, H.K.; Cuéllar-Franca, R.; Azapagic, A. Environmental and economic implications of recovering resources from food waste in a circular economy. *Sci. Total Environ.* **2019**, *693*, 133516. [\[CrossRef\]](#)
103. Slorach, P.C.; Jeswani, H.K.; Cuéllar-Franca, R.; Azapagic, A. Assessing the economic and environmental sustainability of household food waste management in the UK: Current situation and future scenarios. *Sci. Total Environ.* **2020**, *710*, 135580. [\[CrossRef\]](#)
104. Ma, Y.; Liu, Y. Turning food waste to energy and resources towards a great environmental and economic sustainability: An innovative integrated biological approach. *Biotechnol. Adv.* **2019**, *37*, 107414. [\[CrossRef\]](#)
105. Aleisa, E.; Alsaleh, A. Upcycling food waste into animal feed: An environmental assessment based on food waste quantities in different district types in Kuwait. *J. Eng. Res.* **2024**, *13*, 2212–2223. [\[CrossRef\]](#)
106. Salemdieb, R.; zu Ermgassen, E.K.H.J.; Kim, M.H.; Balmford, A.; Al-Tabbaa, A. Environmental and health impacts of using food waste as animal feed: A comparative analysis of food waste management options. *J. Clean. Prod.* **2017**, *140*, 871–880. [\[CrossRef\]](#)
107. Su, Y.; Zhou, S.; Tian, P.; Qi, C.; Xu, Z.; Zhang, Y.; Huh, S.-Y.; Luo, W.; Li, G.; Li, Y. Techno-economic assessment of industrial food waste composting facility: Evaluating bulking agents, processing strategies, and market dynamics. *Bioresour. Technol.* **2024**, *408*, 131210. [\[CrossRef\]](#)
108. Al Mussa Ugak, M.; Mohamad, N.E.; Rajin, M.; Lamaming, J.; Saalah, S.; Yaser, A.Z. Passive aerated in-vessel composting of food waste with the addition of Sabah ragi for campus sustainability: Mass balance, dwarf crape jasmine growth and techno-economic study. *J. Mater. Cycles Waste Manag.* **2023**, *25*, 899–909. [\[CrossRef\]](#)
109. Rashid, M.I.; Shahzad, K. Food waste recycling for compost production and its economic and environmental assessment as circular economy indicators of solid waste management. *J. Clean. Prod.* **2021**, *317*, 128467. [\[CrossRef\]](#)
110. Keng, Z.X.; Chong, S.; Ng, C.G.; Ridzuan, N.I.; Hanson, S.; Pan, G.-T.; Lau, P.L.; Supramaniam, C.V.; Singh, A.; Chin, C.F.; et al. Community-scale composting for food waste: A life-cycle assessment-supported case study. *J. Clean. Prod.* **2020**, *261*, 121220. [\[CrossRef\]](#)

111. Rahmani, A.M.; Hafyan, R.H.; Tyagi, V.K.; Gadkari, S.; Kazmi, A.A.; Ojha, C.S.P. Advanced anaerobic co-digestion of hydrothermally pretreated wheat straw: Process performance, techno-economic and life cycle assessment. *J. Environ. Manag.* **2025**, *373*, 123559. [\[CrossRef\]](#)
112. Chen, Y.; Pinegar, L.; Immonen, J.; Powell, K.M. Conversion of food waste to renewable energy: A techno-economic and environmental assessment. *J. Clean. Prod.* **2023**, *385*, 135741. [\[CrossRef\]](#)
113. Rasheed, R.; Yasar, A.; Wang, Y.; Tabinda, A.B.; Ahmad, S.R.; Tahir, F.; Su, Y. Environmental impact and economic sustainability analysis of a novel anaerobic digestion waste-to-energy pilot plant in Pakistan. *Environ. Sci. Pollut. Res.* **2019**, *26*, 26404–26417. [\[CrossRef\]](#)
114. Yakah, N.; Kwarteng, A.A.; Addy, C.; Yirenkyi, M.; Martin, A.; Simons, A. Techno-Economic Assessment of Municipal Solid Waste (MSW) Incineration in Ghana. *Processes* **2024**, *12*, 1286. [\[CrossRef\]](#)
115. Tong, H.; Shen, Y.; Zhang, J.; Wang, C.-H.; Ge, T.S.; Tong, Y.W. A comparative life cycle assessment on four waste-to-energy scenarios for food waste generated in eateries. *Appl. Energy* **2018**, *225*, 1143–1157. [\[CrossRef\]](#)
116. Escamilla-García, P.E.; Camarillo-López, R.H.; Carrasco-Hernández, R.; Fernández-Rodríguez, E.; Legal-Hernández, J.M. Technical and economic analysis of energy generation from waste incineration in Mexico. *Energy Strategy Rev.* **2020**, *31*, 100542. [\[CrossRef\]](#)
117. Leme, M.M.V.; Rocha, M.H.; Lora, E.E.S.; Venturini, O.J.; Lopes, B.M.; Ferreira, C.H. Techno-economic analysis and environmental impact assessment of energy recovery from Municipal Solid Waste (MSW) in Brazil. *Resour. Conserv. Recycl.* **2014**, *87*, 8–20. [\[CrossRef\]](#)
118. Jeswani, H.K.; Azapagic, A. Assessing the environmental sustainability of energy recovery from municipal solid waste in the UK. *Waste Manag.* **2016**, *50*, 346–363. [\[CrossRef\]](#)
119. Otero Meza, D.D.; Sagastume Gutiérrez, A.; Cabello Eras, J.J.; Salcedo Mendoza, J.; Hernández Ruydiaz, J. Techno-economic and environmental assessment of the landfill gas to energy potential of major Colombian cities. *Energy Convers. Manag.* **2023**, *293*, 117522. [\[CrossRef\]](#)
120. Rahman, T.; Deb, N.; Alam, M.Z.; Moniruzzaman, M.; Miah, M.S.; Horaira, M.A.; Kamal, R. Navigating the contemporary landscape of food waste management in developing countries: A comprehensive overview and prospective analysis. *Heliyon* **2024**, *10*, e33218. [\[CrossRef\]](#)
121. Dong, J.; Tang, Y.; Nzihou, A.; Chi, Y.; Weiss-Hortala, E.; Ni, M. Life cycle assessment of pyrolysis, gasification and incineration waste-to-energy technologies: Theoretical analysis and case study of commercial plants. *Sci. Total Environ.* **2018**, *626*, 744–753. [\[CrossRef\]](#)
122. Wijekoon, P.; Koliyabandara, P.A.; Cooray, A.T.; Lam, S.S.; Athapattu, B.C.L.; Vithanage, M. Progress and prospects in mitigation of landfill leachate pollution: Risk, pollution potential, treatment and challenges. *J. Hazard. Mater.* **2022**, *421*, 126627. [\[CrossRef\]](#)
123. Mia, M.S.; Ahmed, M.M.; Zzaman, W. Valorization of food waste into functional ingredients supports a sustainable strategy for the food industry. *Discov. Food* **2025**, *5*, 275. [\[CrossRef\]](#)
124. Narisetty, V.; Adlakha, N.; Kumar Singh, N.; Dalei, S.K.; Prabhu, A.A.; Nagarajan, S.; Naresh Kumar, A.; Amruthraj Nagoth, J.; Kumar, G.; Singh, V.; et al. Integrated biorefineries for repurposing of food wastes into value-added products. *Bioresour. Technol.* **2022**, *363*, 127856. [\[CrossRef\]](#)
125. Ye, Y.; Guo, W.; Ngo, H.H.; Wei, W.; Cheng, D.; Bui, X.T.; Hoang, N.B.; Zhang, H. Biofuel production for circular bioeconomy: Present scenario and future scope. *Sci. Total Environ.* **2024**, *935*, 172863. [\[CrossRef\]](#)
126. Kwan, T.H.; Pleissner, D.; Lau, K.Y.; Venus, J.; Pommeret, A.; Lin, C.S.K. Techno-economic analysis of a food waste valorization process via microalgae cultivation and co-production of plasticizer, lactic acid and animal feed from algal biomass and food waste. *Bioresour. Technol.* **2015**, *198*, 292–299. [\[CrossRef\]](#) [\[PubMed\]](#)
127. Sharma, H.B.; Vanapalli, K.R.; Samal, B.; Cheela, V.R.S.; Dubey, B.K.; Bhattacharya, J. Circular economy approach in solid waste management system to achieve UN-SDGs: Solutions for post-COVID recovery. *Sci. Total Environ.* **2021**, *800*, 149605. [\[CrossRef\]](#)
128. Ashraf Joolaei, A.; Makian, M.; Prakash, O.; Im, S.; Kang, S.; Kim, D.-H. Effects of particle size on the pretreatment efficiency and subsequent biogas potential of polylactic acid. *Bioresour. Technol.* **2024**, *394*, 130306. [\[CrossRef\]](#)
129. Li, Z.; Jiang, X.; Shi, W.; Yang, D.; Zhao, Y.; Zhou, T. Enhancement of Anaerobic Digestion from Food Waste via Ultrafine Wet Milling Pretreatment: Simulation, Performance, and Mechanisms. *Sustainability* **2024**, *16*, 2933. [\[CrossRef\]](#)
130. Sawarkar, A.N.; Kirti, N.; Tagade, A.; Tekade, S.P. Bioethanol from various types of banana waste: A review. *Bioresour. Technol. Rep.* **2022**, *18*, 101092. [\[CrossRef\]](#)
131. Hernández Pérez, R.; Salgado Delgado, R.; Olarte Paredes, A.; Salgado Delgado, A.; García Hernández, E.; Medrano Valis, A.; Martínez Candia, F. Comparing Acid and Enzymatic Hydrolysis Methods for Cellulose Nanocrystals (CNCs) Obtention from Agroindustrial Rice Husk Waste. *J. Nanotechnol.* **2022**, *2022*, 5882113. [\[CrossRef\]](#)
132. Narisetty, V.; Zhang, L.; Zhang, J.; Sze Ki Lin, C.; Wah Tong, Y.; Loke Show, P.; Kant Bhatia, S.; Misra, A.; Kumar, V. Fermentative production of 2,3-Butanediol using bread waste—A green approach for sustainable management of food waste. *Bioresour. Technol.* **2022**, *358*, 127381. [\[CrossRef\]](#)

133. Manju. Chapter 21—Food wastes for bioethanol production. In *Value-Addition in Agri-food Industry Waste Through Enzyme Technology*; Academic Press: Cambridge, MA, USA, 2023; pp. 315–328. [\[CrossRef\]](#)
134. Taheri, M.E.; Salimi, E.; Saragas, K.; Novakovic, J.; Barampouti, E.M.; Mai, S.; Malamis, D.; Moustakas, K.; Loizidou, M. Effect of pretreatment techniques on enzymatic hydrolysis of food waste. *Biomass Convers. Biorefin.* **2021**, *11*, 219–226. [\[CrossRef\]](#)
135. Werpy, T.; Petersen, G. *Top Value Added Chemicals from Biomass: Volume I—Results of Screening for Potential Candidates from Sugars and Synthesis Gas*; National Renewable Energy Lab. (NREL): Golden, CO, USA, 2004.
136. LBNNet. *UK Top Bio-Based Chemicals Opportunities*; E4tech (UK) Ltd. for LBNNet: London, UK, 2017. Available online: <https://www.bbnet-nibb.co.uk/resource/uk-top-bio-based-chemicals-opportunities> (accessed on 10 July 2025).
137. Kumar, R.S.; Jain, A.; Singh, N.K.; Ghosh, S. Bioethanol production from mixed sugars at a semi-pilot scale through two-step repeated sequential fermentation. *Fuel* **2024**, *357*, 130042. [\[CrossRef\]](#)
138. Abedi, E.; Hashemi, S.M.B. Lactic acid production—Producing microorganisms and substrates sources-state of art. *Heliyon* **2020**, *6*, e04974. [\[CrossRef\]](#)
139. Tran, V.G.; Mishra, S.; Bhagwat, S.S.; Shafaei, S.; Shen, Y.; Allen, J.L.; Crosly, B.A.; Tan, S.-I.; Fatma, Z.; Rabinowitz, J.D.; et al. An end-to-end pipeline for succinic acid production at an industrially relevant scale using *Issatchenkia orientalis*. *Nat. Commun.* **2023**, *14*, 6152. [\[CrossRef\]](#) [\[PubMed\]](#)
140. Mailaram, S.; Narisetty, V.; Ranade, V.V.; Kumar, V.; Maity, S.K. Techno-Economic Analysis for the Production of 2,3-Butanediol from Brewers’ Spent Grain Using Pinch Technology. *Ind. Eng. Chem. Res.* **2022**, *61*, 2195–2205. [\[CrossRef\]](#)
141. Hou, X.; From, N.; Angelidaki, I.; Huijgen, W.J.J.; Bjerre, A.-B. Butanol fermentation of the brown seaweed *Laminaria digitata* by *Clostridium beijerinckii* DSM-6422. *Bioresour. Technol.* **2017**, *238*, 16–21. [\[CrossRef\]](#)
142. Bhuiya, M.M.K.; Rasul, M.; Khan, M.; Ashwath, N.; Mofijur, M. Comparison of oil extraction between screw press and solvent (n-hexane) extraction technique from beauty leaf (*Calophyllum inophyllum* L.) feedstock. *Ind. Crops Prod.* **2020**, *144*, 112024. [\[CrossRef\]](#)
143. He, Y.; Huang, Z.; Zhong, C.; Guo, Z.; Chen, B. Pressurized liquid extraction with ethanol as a green and efficient technology to lipid extraction of *Isochrysis* biomass. *Bioresour. Technol.* **2019**, *293*, 122049. [\[CrossRef\]](#)
144. Kanda, H.; Hoshino, R.; Murakami, K.; Wahyudiono; Zheng, Q.; Goto, M. Lipid extraction from microalgae covered with biomineralized cell walls using liquefied dimethyl ether. *Fuel* **2020**, *262*, 116590. [\[CrossRef\]](#)
145. Pleissner, D.; Kwan, T.H.; Lin, C.S.K. Fungal hydrolysis in submerged fermentation for food waste treatment and fermentation feedstock preparation. *Bioresour. Technol.* **2014**, *158*, 48–54. [\[CrossRef\]](#)
146. Carmona-Cabello, M.; García, I.L.; Papadaki, A.; Tsouko, E.; Koutinas, A.; Dorado, M.P. Biodiesel production using microbial lipids derived from food waste discarded by catering services. *Bioresour. Technol.* **2021**, *323*, 124597. [\[CrossRef\]](#) [\[PubMed\]](#)
147. Kim, J.Y.; Yeom, S.H. Optimization of Biodiesel Production from Waste Coffee Grounds by Simultaneous Lipid Extraction and Transesterification. *Biotechnol. Bioprocess Eng.* **2020**, *25*, 320–326. [\[CrossRef\]](#)
148. Rajendran, N.; Han, J. Integrated polylactic acid and biodiesel production from food waste: Process synthesis and economics. *Bioresour. Technol.* **2022**, *343*, 126119. [\[CrossRef\]](#)
149. Bhuana, D.S.; Qadariyah, L.; Panjaitan, R.; Mahfud, M. Optimization of biodiesel production from *Chlorella* sp through in-situ microwave-assisted acid-catalyzed trans-esterification. *IOP Conf. Ser. Mater. Sci. Eng.* **2020**, *732*, 012004. [\[CrossRef\]](#)
150. Shinde, K.; Kaliaguine, S. A Comparative Study of Ultrasound Biodiesel Production Using Different Homogeneous Catalysts. *ChemEngineering* **2019**, *3*, 18. [\[CrossRef\]](#)
151. Mandari, V.; Devarai, S.K. Biodiesel Production Using Homogeneous, Heterogeneous, and Enzyme Catalysts via Transesterification and Esterification Reactions: A Critical Review. *BioEnergy Res.* **2022**, *15*, 935–961. [\[CrossRef\]](#) [\[PubMed\]](#)
152. Kapil, A.; Wilson, K.; Lee, A.F.; Sadhukhan, J. Kinetic Modeling Studies of Heterogeneously Catalyzed Biodiesel Synthesis Reactions. *Ind. Eng. Chem. Res.* **2011**, *50*, 4818–4830. [\[CrossRef\]](#)
153. Karmee, S.K.; Linardi, D.; Lee, J.; Lin, C.S.K. Conversion of lipid from food waste to biodiesel. *Waste Manag.* **2015**, *41*, 169–173. [\[CrossRef\]](#)
154. Kamal, H.; Le, C.F.; Salter, A.M.; Ali, A. Extraction of protein from food waste: An overview of current status and opportunities. *Compr. Rev. Food Sci. Food Saf.* **2021**, *20*, 2455–2475. [\[CrossRef\]](#)
155. Zaelani, B.F.D.; Safithri, M.; Tarman, K.; Setyaningsih, I.; Meydia. Collagen isolation with acid soluble method from the skin of Red Snapper (*Lutjanus* sp.). *IOP Conf. Ser. Earth Environ. Sci.* **2019**, *241*, 012033. [\[CrossRef\]](#)
156. Zhang, Y.; Tu, D.; Shen, Q.; Dai, Z. Fish Scale Valorization by Hydrothermal Pretreatment Followed by Enzymatic Hydrolysis for Gelatin Hydrolysate Production. *Molecules* **2019**, *24*, 2998. [\[CrossRef\]](#)
157. Choi, Y.H.; Verpoorte, R. Green solvents for the extraction of bioactive compounds from natural products using ionic liquids and deep eutectic solvents. *Curr. Opin. Food Sci.* **2019**, *26*, 87–93. [\[CrossRef\]](#)
158. Görgüç, A.; Özer, P.; Yılmaz, F.M. Microwave-assisted enzymatic extraction of plant protein with antioxidant compounds from the food waste sesame bran: Comparative optimization study and identification of metabolomics using LC/Q-TOF/MS. *J. Food Process. Preserv.* **2020**, *44*, e14304. [\[CrossRef\]](#)

159. Eze, O.F.; Chatzifragkou, A.; Charalampopoulos, D. Properties of protein isolates extracted by ultrasonication from soybean residue (okara). *Food Chem.* **2022**, *368*, 130837. [\[CrossRef\]](#)
160. Barrios, C.; Fernández-Delgado, M.; López-Linares, J.C.; García-Cubero, M.T.; Coca, M.; Lucas, S. A techno-economic perspective on a microwave extraction process for efficient protein recovery from agri-food wastes. *Ind. Crops Prod.* **2022**, *186*, 115166. [\[CrossRef\]](#)
161. Shahid, K.; Srivastava, V.; Sillanpää, M. Protein recovery as a resource from waste specifically via membrane technology—From waste to wonder. *Environ. Sci. Pollut. Res.* **2021**, *28*, 10262–10282. [\[CrossRef\]](#)
162. Navaf, M.; Sunooj, K.V.; Aaliya, B.; Sudheesh, C.; Akhila, P.P.; Mir, S.A.; Nemtanu, M.R.; George, J.; Lackner, M.; Mousavi Khaneghah, A. Contemporary insights into the extraction, functional properties, and therapeutic applications of plant proteins. *J. Agric. Food Res.* **2023**, *14*, 100861. [\[CrossRef\]](#)
163. Sadhukhan, J.; Gadkari, S.; Martinez-Hernandez, E.; Ng, K.S.; Shemfe, M.; Torres-Garcia, E.; Lynch, J. Novel macroalgae (seaweed) biorefinery systems for integrated chemical, protein, salt, nutrient and mineral extractions and environmental protection by green synthesis and life cycle sustainability assessments. *Green Chem.* **2019**, *21*, 2635–2655. [\[CrossRef\]](#)
164. Ladakis, D.; Stylianou, E.; Ioannidou, S.-M.; Koutinas, A.; Pateraki, C. Biorefinery development, techno-economic evaluation and environmental impact analysis for the conversion of the organic fraction of municipal solid waste into succinic acid and value-added fractions. *Bioresour. Technol.* **2022**, *354*, 127172. [\[CrossRef\]](#)
165. Kwan, T.H.; Hu, Y.; Lin, C.S.K. Valorisation of food waste via fungal hydrolysis and lactic acid fermentation with *Lactobacillus casei* Shirota. *Bioresour. Technol.* **2016**, *217*, 129–136. [\[CrossRef\]](#)
166. Lobeda, K.; Jin, Q.; Wu, J.; Zhang, W.; Huang, H. Lactic acid production from food waste hydrolysate by *Lactobacillus pentosus*: Focus on nitrogen supplementation, initial sugar concentration, pH, and fed-batch fermentation. *J. Food Sci.* **2022**, *87*, 3071–3083. [\[CrossRef\]](#)
167. Cox, R.; Narisetty, V.; Nagarajan, S.; Agrawal, D.; Ranade, V.V.; Saloniitis, K.; Venus, J.; Kumar, V. High-Level fermentative production of Lactic acid from bread waste under Non-sterile conditions with a circular biorefining approach and zero waste discharge. *Fuel* **2022**, *313*, 122976. [\[CrossRef\]](#)
168. Li, C.; Ong, K.L.; Yang, X.; Lin, C.S.K. Bio-refinery of waste streams for green and efficient succinic acid production by engineered *Yarrowia lipolytica* without pH control. *Chem. Eng. J.* **2019**, *371*, 804–812. [\[CrossRef\]](#)
169. Yang, X.; Wang, H.; Li, C.; Lin, C.S.K. Restoring of Glucose Metabolism of Engineered *Yarrowia lipolytica* for Succinic Acid Production via a Simple and Efficient Adaptive Evolution Strategy. *J. Agric. Food Chem.* **2017**, *65*, 4133–4139. [\[CrossRef\]](#)
170. Gadkari, S.; Kumar, D.; Qin, Z.-h.; Ki Lin, C.S.; Kumar, V. Life cycle analysis of fermentative production of succinic acid from bread waste. *Waste Manag.* **2021**, *126*, 861–871. [\[CrossRef\]](#)
171. Teresa Sponza, D.; Öztekin, R. 1-Butanol Production from the Food Wastes in Dokuz Eylül University Campus Buca-Izmir, Turkey. *Open J. Case Rep.* **2022**, *3*, 1–5.
172. Jin, Q.; An, Z.; Damle, A.; Poe, N.; Wu, J.; Wang, H.; Wang, Z.; Huang, H. High Acetone-Butanol-Ethanol Production from Food Waste by Recombinant *Clostridium saccharoperbutylacetonicum* in Batch and Continuous Immobilized-Cell Fermentation. *ACS Sustain. Chem. Eng.* **2020**, *8*, 9822–9832. [\[CrossRef\]](#)
173. Huang, H.; Singh, V.; Qureshi, N. Butanol production from food waste: A novel process for producing sustainable energy and reducing environmental pollution. *Biotechnol. Biofuels* **2015**, *8*, 147. [\[CrossRef\]](#)
174. Yu, D.; O’Hair, J.; Poe, N.; Jin, Q.; Pinton, S.; He, Y.; Huang, H. Conversion of Food Waste into 2,3-Butanediol via Thermophilic Fermentation: Effects of Carbohydrate Content and Nutrient Supplementation. *Foods* **2022**, *11*, 169. [\[CrossRef\]](#)
175. Jain, S. Biodiesel production from food waste using insitu transesterification method. *Sustain. Energy Technol. Assess.* **2023**, *58*, 103380. [\[CrossRef\]](#)
176. Rajendran, N.; Kang, D.; Han, J.; Gurunathan, B. Process optimization, economic and environmental analysis of biodiesel production from food waste using a citrus fruit peel biochar catalyst. *J. Clean. Prod.* **2022**, *365*, 132712. [\[CrossRef\]](#)
177. Parvari, E.; Mahajan, D.; Hewitt, E.L. A Review of Biomass Pyrolysis for Production of Fuels: Chemistry, Processing, and Techno-Economic Analysis. *Biomass* **2025**, *5*, 54. [\[CrossRef\]](#)
178. Zaharioiu, A.M.; Şandru, C.; Ionete, E.I.; Marin, F.; Ionete, R.E.; Soare, A.; Constantinescu, M.; Bucura, F.; Niculescu, V.-C. Eco-Friendly Alternative Disposal through the Pyrolysis Process of Meat and Bone Meal. *Materials* **2022**, *15*, 6593. [\[CrossRef\]](#)
179. Fadhil, A.B.; Ahmed, A.I.; Salih, H.A. Production of liquid fuels and activated carbons from fish waste. *Fuel* **2017**, *187*, 435–445. [\[CrossRef\]](#)
180. Kim, S.; Lee, Y.; Andrew Lin, K.-Y.; Hong, E.; Kwon, E.E.; Lee, J. The valorization of food waste via pyrolysis. *J. Clean. Prod.* **2020**, *259*, 120816. [\[CrossRef\]](#)
181. Elgazar, Y.G.; Khalifeh, H.A.; Alkhedher, M.; Ramadan, M. A review of hydrogen production from food waste through gasification process. *Int. J. Hydrogen Energy* **2024**, *67*, 959–969. [\[CrossRef\]](#)
182. Mirzaei, R.; Tavakoli, O. Sustainable hydrogen production via subcritical and supercritical water gasification of food waste: An optimization and reaction pathway study. *J. Energy Inst.* **2026**, *125*, 102427. [\[CrossRef\]](#)

183. Raizada, A.; Yadav, S.; Tripathi, M.; Misra, S.; Mohanty, P. Food waste treatment using in situ gasification after pyrolysis to produce hydrogen-rich syngas. *Biomass Convers. Biorefin.* **2023**, *13*, 9689–9699. [\[CrossRef\]](#)
184. Raizada, A.; Shukla, A.; Yadav, S.; Modak, S.; Katiyar, P. Food Waste Ash Supported Nickel Catalyst to Steam Gasification of Food Waste for Enhanced Tar Reduction and Hydrogen Production. *BioEnergy Res.* **2025**, *18*, 22. [\[CrossRef\]](#)
185. Raizada, A.; Shukla, A.; Yadav, S.; Katiyar, P.; Kumar, R. Enhancement of H₂ production via catalytic steam gasification of food waste as feedstock and its ash as a support and promoter for Ni catalyst. *Int. J. Hydrogen Energy* **2024**, *60*, 272–281. [\[CrossRef\]](#)
186. Sharma, T.; Hakeem, I.G.; Gupta, A.B.; Joshi, J.; Shah, K.; Vuppaladadiyam, A.K.; Sharma, A. Parametric influence of process conditions on thermochemical techniques for biochar production: A state-of-the-art review. *J. Energy Inst.* **2024**, *113*, 101559. [\[CrossRef\]](#)
187. Liu, M.; Zeng, Y. Key Processing Factors in Hydrothermal Liquefaction and Their Impacts on Corrosion of Reactor Alloys. *Sustainability* **2023**, *15*, 9317. [\[CrossRef\]](#)
188. Tito, E.; Marcolongo, C.A.; Pipitone, G.; Monteverde, A.H.A.; Bensaid, S.; Pirone, R. Understanding the effect of heating rate on hydrothermal liquefaction: A comprehensive investigation from model compounds to a real food waste. *Bioresour. Technol.* **2024**, *396*, 130446. [\[CrossRef\]](#)
189. Bayat, H.; Dehghanizadeh, M.; Jarvis, J.M.; Brewer, C.E.; Jena, U. Hydrothermal Liquefaction of Food Waste: Effect of Process Parameters on Product Yields and Chemistry. *Front. Sustain. Food Syst.* **2021**, *5*, 658592. [\[CrossRef\]](#)
190. Brilovich Mosseri, M.; Duenyas, A.; Cohen, E.M.A.; Vitkin, E.; Steinbruch, E.; Epstein, M.; Kribus, A.; Gozin, M.; Golberg, A. Hydrothermal liquefaction of representative to Israel food waste model. *Energy Convers. Manag. X* **2023**, *20*, 100475. [\[CrossRef\]](#)
191. Etezadi, R.; Zhao, L.; Tsotsis, T. Chapter 18—Syngas from food waste. In *Advances in Synthesis Gas: Methods, Technologies and Applications*; Rahimpour, M.R., Makarem, M.A., Meshksar, M., Eds.; Elsevier: Amsterdam, The Netherlands, 2023; Volume 1, pp. 439–455. [\[CrossRef\]](#)
192. Kane, S.; Ryan, C. Biochar from food waste as a sustainable replacement for carbon black in upcycled or compostable composites. *Compos. Part C Open Access* **2022**, *8*, 100274. [\[CrossRef\]](#)
193. Oyedun, A.O.; Patel, M.; Kumar, M.; Kumar, A. The Upgrading of Bio-Oil via Hydrodeoxygenation. In *Chemical Catalysts for Biomass Upgrading*; John Wiley & Sons: Hoboken, NJ, USA, 2020; pp. 35–60. [\[CrossRef\]](#)
194. Mei, D.; Hu, Q.; Zhao, W.; Dai, S.; Wu, W.; Feng, P. Combustion performances evaluation of bio-oil upgraded via catalytic cracking of coconut oil. *Energy Sources Part A Recovery Util. Environ. Eff.* **2026**, *48*, 2637783. [\[CrossRef\]](#)
195. Lin, P.; Yi, W.; Zhang, D.; Wang, F.; Fu, P.; Duan, X.; Sheng, Y. Hydrogen production from light bio-oil: Effect of bio-oil separation processes on catalytic steam reforming. *Int. J. Hydrogen Energy* **2025**, *186*, 152044. [\[CrossRef\]](#)
196. Motta, I.L.; Marchesan, A.N.; Maciel Filho, R.; Maciel, M.R.W. Syngas cleaning and conditioning in biomass gasification plants: A review of technologies, bibliometric trends, and future directions. *Int. J. Hydrogen Energy* **2025**, *154*, 150234. [\[CrossRef\]](#)
197. Danesh, P.; Prussi, M.; Salimbeni, A.; Negro, V.; Chiaramonti, D. Review on Biochar Upgrading Methods for Its Application in Thermochemical Conversion Processes and Critical Materials Recovery. *Sustainability* **2025**, *17*, 10194. [\[CrossRef\]](#)
198. Elkamel, A.; Kim, K.; Hourfar, F.; Laljee, M.M.; Fowler, M. Optimal and sustainable design of integrated biorefineries for microalgae and municipal solid waste processing. *J. Clean. Prod.* **2025**, *519*, 145938. [\[CrossRef\]](#)
199. Criado, A.; Martín, M. Integrated Multiproduct Facility for the Production of Chemicals, Food, and Utilities from Oranges. *Ind. Eng. Chem. Res.* **2020**, *59*, 7722–7731. [\[CrossRef\]](#)
200. Mailaram, S.; Narisetty, V.; Maity, S.K.; Gadkari, S.; Thakur, V.K.; Russell, S.; Kumar, V. Lactic acid and biomethane production from bread waste: A techno-economic and profitability analysis using pinch technology. *Sustain. Energy Fuels* **2023**, *7*, 3034–3046. [\[CrossRef\]](#)
201. Hafyan, R.H.; Sadhukhan, J.; Gadkari, S. Multi-objective optimization of bread waste valorization: A framework for integrated food waste management. *Resour. Conserv. Recycl.* **2026**, *229*, 108871. [\[CrossRef\]](#)
202. Kumar, V.; Brancoli, P.; Narisetty, V.; Wallace, S.; Charalampopoulos, D.; Dubey, B.K.; Kumar, G.; Bhatnagar, A.; Bhatia, S.K.; Taherzadeh, M.J. Bread waste—A potential feedstock for sustainable circular biorefineries. *Bioresour. Technol.* **2022**, *369*, 128449. [\[CrossRef\]](#)
203. Soni, R.; Bhardwaj, A.; Jarangal, L.P.S. Bread waste and mitigation strategies: A review. In *Proceedings of the IOP Conference Series: Materials Science and Engineering*; IOP Publishing: Bristol, UK, 2022; Volume 1248, p. 012010. [\[CrossRef\]](#)
204. Valipour, M.; Mafakheri, F.; Gagnon, B.; Prinz, R.; Bergström, D.; Brown, M.; Wang, C. Integrating bio-hubs in biomass supply chains: Insights from a systematic literature review. *J. Clean. Prod.* **2024**, *467*, 142930. [\[CrossRef\]](#)
205. Chen, C.-S.; Narani, A.; Daniyar, A.; McCauley, J.; Brown, S.; Pray, T.; Tanjore, D. Ensemble models of feedstock blend ratios to minimize supply chain risk in bio-based manufacturing. *Biochem. Eng. J.* **2022**, *181*, 107896. [\[CrossRef\]](#)
206. Ehr Gott, M.; Köksalan, M.; Kadziński, M.; Deb, K. Fifty years of multi-objective optimization and decision-making: From mathematical programming to evolutionary computation. *Eur. J. Oper. Res.* **2026**, *330*, 1–25. [\[CrossRef\]](#)

207. Abbas, S.; Robinson, A.J.; Papadokonstantakis, S. Superstructure configuration and optimization of the biofuel production perspectives in Austria. In *Computer Aided Chemical Engineering*; Kokossis, A.C., Georgiadis, M.C., Pistikopoulos, E., Eds.; Elsevier: Amsterdam, The Netherlands, 2023; Volume 52, pp. 619–624. [\[CrossRef\]](#)
208. Sadhukhan, J.; Sen, S.; Randriamahefasoa, T.M.S.; Gadkari, S. Energy System Optimization for Net-Zero Electricity. *Digit. Chem. Eng.* **2022**, *3*, 100026. [\[CrossRef\]](#)
209. Krishnan, R.; Arshinder, K.; Agarwal, R. Robust optimization of sustainable food supply chain network considering food waste valorization and supply uncertainty. *Comput. Ind. Eng.* **2022**, *171*, 108499. [\[CrossRef\]](#)
210. Amin, H.; Rizwan, M.; Mukhtar, M.; Zaman, M.; Naqvi, S.R.; Elkamel, A.; Shehzad, K. Evaluation of optimal technology for the sustainable processing of municipal solid waste employing MINLP model: A case study of Pakistan. In *Energy Systems*; Springer: Berlin/Heidelberg, Germany, 2024. [\[CrossRef\]](#)
211. Giuliano, A.; Poletto, M.; Barletta, D. Process optimization of a multi-product biorefinery: The effect of biomass seasonality. *Chem. Eng. Res. Des.* **2016**, *107*, 236–252. [\[CrossRef\]](#)
212. Sadhukhan, J.; Ng, K.S.; Hernandez, E.M. Life Cycle Assessment. In *Biorefineries and Chemical Processes*; John Wiley & Sons: Hoboken, NJ, USA, 2014; pp. 93–146. [\[CrossRef\]](#)
213. Hafyan, R.H.; Bhullar, L.K.; Mahadzir, S.; Bilad, M.R.; Nordin, N.A.H.; Wirzal, M.D.H.; Putra, Z.A.; Rangaiah, G.P.; Abdullah, B. Integrated Biorefinery of Empty Fruit Bunch from Palm Oil Industries to Produce Valuable Biochemicals. *Processes* **2020**, *8*, 868. [\[CrossRef\]](#)
214. Sadhukhan, J.; Sen, S.; Gadkari, S. The Mathematics of life cycle sustainability assessment. *J. Clean. Prod.* **2021**, *309*, 127457. [\[CrossRef\]](#)
215. Saleem, N.N.; Yin, N.L.; Andiappan, V. Process Synthesis of Biorefineries under Uncertain Feedstock Conditions Based on Hurwicz Criterion. *Process Integr. Optim. Sustain.* **2021**, *5*, 231–246. [\[CrossRef\]](#)
216. Bairamzadeh, S.; Saidi-Mehrabad, M.; Pishvae, M.S. Modelling different types of uncertainty in biofuel supply network design and planning: A robust optimization approach. *Renew. Energy* **2018**, *116*, 500–517. [\[CrossRef\]](#)
217. Mavromatidis, G.; Orehounig, K.; Carmeliet, J. Design of distributed energy systems under uncertainty: A two-stage stochastic programming approach. *Appl. Energy* **2018**, *222*, 932–950. [\[CrossRef\]](#)
218. Xie, C.; Tian, Y.; Wu, L. Multiperiod Two-Stage Stochastic Programming of Supply Chain for Co-Processing System of Bio-Oil and Heavy Oil. *ACS Sustain. Chem. Eng.* **2023**, *11*, 3850–3860. [\[CrossRef\]](#)
219. Huynh, D.; Ierapetritou, M. Biorefinery superstructure optimization under carbon pricing policies using stochastic programming. *Appl. Energy* **2024**, *376*, 124283. [\[CrossRef\]](#)
220. He, W.; Zhao, J.; Zhao, L.; Li, Z.; Yang, M.; Liu, T. Data-driven two-stage distributionally robust optimization for refinery planning under uncertainty. *Chem. Eng. Sci.* **2023**, *269*, 118466. [\[CrossRef\]](#)
221. Jabbarzadeh, A.; Shamsi, M. Designing a resilient and sustainable multi-feedstock bioethanol supply chain: Integration of mathematical modeling and machine learning. *Appl. Energy* **2025**, *377*, 123794. [\[CrossRef\]](#)
222. Sadeghi Darvazeh, S.; Mansoori Mooseloo, F.; Gholian-Jouybari, F.; Amiri, M.; Bonakdari, H.; Hajiaghahi-Keshteli, M. Data-driven robust optimization to design an integrated sustainable forest biomass-to-electricity network under disjunctive uncertainties. *Appl. Energy* **2024**, *356*, 122404. [\[CrossRef\]](#)
223. Huang, X.; Ji, L.; Xie, Y.; Luo, Z. Robust optimization of regional biomass supply chain system design and operation with data-driven uncertainties. *Food Bioprod. Process.* **2025**, *149*, 176–189. [\[CrossRef\]](#)
224. Zhang, Y.; Liu, Y.; Shu, S.; Zheng, F.; Huang, Z. A data-driven distributionally robust optimization model for multi-energy coupled system considering the temporal-spatial correlation and distribution uncertainty of renewable energy sources. *Energy* **2021**, *216*, 119171. [\[CrossRef\]](#)
225. Mukhtar, M.; Rizwan, M.; Ullah, A.; Elkamel, A.; Raza Naqvi, S.; Zaman, M. Municipal solid waste supply chain optimization for value-added product development under uncertainty. *Waste Manag. Bull.* **2025**, *3*, 66–75. [\[CrossRef\]](#)
226. Huang, X.; Ji, L.; Yin, J.; Huang, G. Optimal design and robust operational management of regional bioethanol supply chain with various technological choices and uncertainty fusions. *Comput. Chem. Eng.* **2024**, *182*, 108565. [\[CrossRef\]](#)
227. Co, D.V.Y.; Lim, A.S.O.; Ng, R.C.N.; Sy, K.W.V.; San Juan, J.L. Integrating heterogenous robustness levels to the multi-objective target-oriented robust optimization of a microalgal biorefinery. *J. Clean. Prod.* **2024**, *475*, 143675. [\[CrossRef\]](#)
228. Theozzo, B.; Teles dos Santos, M. A robust optimization framework for forest biorefineries design considering uncertainties on biomass growth and product selling prices. *Comput. Chem. Eng.* **2023**, *175*, 108256. [\[CrossRef\]](#)
229. Luo, Y.; Ierapetritou, M. Multifeedstock and Multiproduct Process Design Using Neural Network Surrogate Flexibility Constraints. *Ind. Eng. Chem. Res.* **2023**, *62*, 2067–2079. [\[CrossRef\]](#)
230. Zarrinpoor, N. Bioenergy production from agro-livestock waste under uncertainty: A sustainable network design. *Biomass Convers. Biorefin.* **2024**, *14*, 1149–1172. [\[CrossRef\]](#)

231. Umar, M.; Tayyab, M.; Chaudhry, H.R.; Su, C.-W. Navigating epistemic uncertainty in third-generation biodiesel supply chain management through robust optimization for economic and environmental performance. *Ann. Oper. Res.* **2023**, *359*, 1485–1524. [\[CrossRef\]](#)
232. Ahmadvand, S.; Sowlati, T. A robust optimization model for tactical planning of the forest-based biomass supply chain for syngas production. *Comput. Chem. Eng.* **2022**, *159*, 107693. [\[CrossRef\]](#)
233. Zarei, M.; Shams, M.H.; Niaz, H.; Won, W.; Lee, C.-J.; Liu, J.J. Risk-based multistage stochastic mixed-integer optimization for biofuel supply chain management under multiple uncertainties. *Renew. Energy* **2022**, *200*, 694–705. [\[CrossRef\]](#)
234. Habib, M.S.; Omair, M.; Ramzan, M.B.; Chaudhary, T.N.; Farooq, M.; Sarkar, B. A robust possibilistic flexible programming approach toward a resilient and cost-efficient biodiesel supply chain network. *J. Clean. Prod.* **2022**, *366*, 132752. [\[CrossRef\]](#)
235. Abdali, H.; Sahebi, H.; Pishvae, M. A sustainable robust optimization model to design a sugarcane-based bioenergy supply network: A case study. *Chem. Eng. Res. Des.* **2022**, *180*, 265–284. [\[CrossRef\]](#)
236. Bhosekar, A.; Athaley, A.; Ierapetritou, M. Multiobjective Modular Biorefinery Configuration under Uncertainty. *Ind. Eng. Chem. Res.* **2021**, *60*, 12956–12969. [\[CrossRef\]](#)
237. Iacovidou, E.; Voulvoulis, N. A multi-criteria sustainability assessment framework: Development and application in comparing two food waste management options using a UK region as a case study. *Environ. Sci. Pollut. Res.* **2018**, *25*, 35821–35834. [\[CrossRef\]](#)
238. Sanaei, S.; Chambost, V.; Stuart, P.R. Systematic assessment of triticale-based biorefinery strategies: Sustainability assessment using multi-criteria decision-making (MCDM). *Biofuels Bioprod. Biorefining* **2018**, *12*, S73–S86. [\[CrossRef\]](#)
239. Makarichi, L.; Techato, K.-a.; Jutidamrongphan, W. Material flow analysis as a support tool for multi-criteria analysis in solid waste management decision-making. *Resour. Conserv. Recycl.* **2018**, *139*, 351–365. [\[CrossRef\]](#)
240. Taherdoost, H.; Madanchian, M. Multi-Criteria Decision Making (MCDM) Methods and Concepts. *Encyclopedia* **2023**, *3*, 77–87. [\[CrossRef\]](#)
241. Zarei, M.; Cherif, A.; Yoon, H.-J.; Liu, J.J.; Lee, C.-J. Optimal design of a biofuel supply chain using an augmented multi-objective and TOPSIS method. *Green Chem.* **2023**, *25*, 4067–4075. [\[CrossRef\]](#)
242. Yadav, S.; Choudhary, A.K.; Yadav, P.; Pal, D.B. Lignocellulosic biomass gasification for bio-circular economy sustainability: A multiple criteria analysis framework. *Biomass Convers. Biorefin.* **2025**, *15*, 30667–30677. [\[CrossRef\]](#)
243. Nath, B.; Basumatary, B.; Wary, N.; Basumatary, U.R.; Basumatary, J.; Rokhum, S.L.; Azam, M.; Min, K.; Basumatary, S. Agricultural Waste-Based Heterogeneous Catalyst for the Production of Biodiesel: A Ranking Study via the VIKOR Method. *Int. J. Energy Res.* **2023**, *2023*, 7208754. [\[CrossRef\]](#)
244. Akgün, M.K.; Soygüder, S. A Hybrid Decision-Making Framework for Evaluating mHealth App Quality: Integrating Fuzzy BWM with the Weighted Heronian Mean. *Int. J. Fuzzy Syst.* **2025**. [\[CrossRef\]](#)
245. Malefaki, S.; Markatos, D.; Filippatos, A.; Pantelakis, S. A Comparative Analysis of Multi-Criteria Decision-Making Methods and Normalization Techniques in Holistic Sustainability Assessment for Engineering Applications. *Aerospace* **2025**, *12*, 100. [\[CrossRef\]](#)
246. Wang, W.; Cao, Y.; Deveci, M.; Wu, Q. An extensible complex spherical fuzzy decision making model based selection framework for the food waste treatment method. *Appl. Soft Comput.* **2024**, *150*, 111068. [\[CrossRef\]](#)
247. Rani, P.; Mishra, A.R.; Krishankumar, R.; Ravichandran, K.S.; Kar, S. Multi-criteria food waste treatment method selection using single-valued neutrosophic-CRITIC-MULTIMOORA framework. *Appl. Soft Comput.* **2021**, *111*, 107657. [\[CrossRef\]](#)

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.



DSPACE

<https://dspace.org/>

Food waste valorization: guidance for integrating sustainable management strategies

Hafyan, Rendra Hakim; Kumar, Vinod; Maity, Sunil K.; Sadhukhan, Jhuma; Gadkari, Siddharth

2026-06-01

MDPI

<https://doi.org/10.3390/app16115349>

Hafyan RH, Kumar V, Maity SK, et al., (2026) Food waste valorization: guidance for integrating sustainable management strategies. Applied Sciences, Volume 16, Issue 11, June 2026, Article number 5349