Green Energy and Fuel Research

Review

Sustaining Food Waste for Energy Conversion: A Mini Review

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Abstract: The escalating global food waste crisis poses significant environmental challenges and resource losses, with approximately one-third of all food produced for human consumption wasted each year. This review explores the innovative conversion of food waste into bioenergy by highlighting various technologies such as hydrothermal conversion, gasification coupled with Fischer-Tropsch synthesis, bio-electrochemical, and synthetic biology and metabolic engineering. These methods help to mitigate greenhouse gas emissions associated with food waste disposal and also provide renewable energy alternatives that can help reduce dependency on fossil fuels. Recent advancements in these technologies have demonstrated improved efficiency, greater feedstock flexibility, and enhanced economic viability, making food waste essential in the pursuit of a circular bioeconomy. This review emphasizes the importance of matching and screening different types of food waste for energy conversion, which is crucial for optimizing resource recovery and maximizing energy output. By examining the latest developments in food waste-to-bioenergy technologies, this review also aims to underscore the potential of food waste as a valuable resource and contribute to sustainable waste management and energy security efforts. The transformative potential of food waste conversion technologies in addressing the pressing global food waste crisis were evaluated. Adopting these methods promotes a circular bioeconomy where waste is valued as a resource, not a burden. The integration of these technologies into existing food waste management systems will be crucial for achieving energy security, mitigating environmental impacts, and promoting sustainable resource utilization. As we face the challenges of food waste, these solutions may represent a critical pathway toward a more sustainable future.

Keywords: food waste; bioenergy; advance technologies; renewable energy; waste-to-bioenergy

1. Introduction

The increase in global population and urbanization has led to a significant rise in food production and consumption, resulting in a significant increase in food waste. According to the Food and Agriculture Organization (FAO), approximately one-third of all food produced for human consumption is wasted, which amounts to about 1.05 billion metric tons annually in 2022. The food waste generated by household, food service, and retail sector of 631 million metric tons, 290 million metric tons, and 131 million metric tons, respectively [1]. This enormous quantity of food waste represents a significant loss of resources, including water, energy, and labor. While food waste also contributes to environmental pollution when disposed of in landfills, where it decomposes and emits greenhouse gases such as methane. Decomposing organic matter in landfills produces methane, a greenhouse gas with a global warming potential over 25 times that of carbon dioxide over a 100-year period [2–4]. Recent studies have indicated that reducing food waste could lead to the most significant decreases in greenhouse gas emissions in Latin America and the Caribbean (24.6 Mt CO_2 eq.), followed by Southern Asia (10.7 Mt CO_2 eq.) and Sub-Saharan Africa (5.5 Mt CO_2 eq.) [5]. Converting food waste into bioenergy offers a sustainable solution to mitigate these problems. However, bioenergy production faces challenges such as technological limitations, economic viability, and the need for supportive policies to encourage adoption and investment in innovative waste management strategies.

In recent years, the conversion of food waste into bioenergy demonstrated as a sustainable and renewable energy source that can helps to reduce the dependency on fossil fuels, lower greenhouse gas emissions, and promote a circular bioeconomy [6–8]. The concept of transforming food waste into bioenergy involves various technologies that can convert food waste into valuable biofuels, such as biogas, bio-oil, biochar, and syngas. A previous study by Chen et al. [9] reported that food waste-derived bio-oil achieved a heating value of 34.79 MJ/kg, with a liquefaction energy recovery of 50.3%. These biofuels can be utilized for heating, electricity generation, and transportation, thereby offering an eco-friendly alternative to conventional energy sources. For instance, Mahmudul et al. [10] has reported that the conversion of food waste into biogas can produce electricity of 52.36 GW and 554.4 TJ heat per year through anaerobic digestion. This study also found that food waste can produce biomethane of 47% and can reduce greenhouse gas emissions up to 414,898 tonnes. However, these traditional processes have certain limitations, such as the generation of secondary waste (e.g., sludge) and the need for extensive pre-processing (e.g., mechanical size reduction, dewatering, or chemical pretreatment) of feedstocks.

Recent advancements in food waste management have introduced innovative methods such as hydrothermal liquefaction (HTL), hydrothermal carbonization (HTC), hydrothermal gasification (HTG), gasification coupled with Fischer-Tropsch (FT) synthesis, bio-electrochemical conversion, and synthetic biology and metabolic engineering. These new technologies offer higher efficiency, greater feedstock flexibility, and improved environmental performance, making them a promising solutions for sustainable biofuel production from food waste. For instance, integrated systems that combine anaerobic digestion with other technologies, such as anaerobic co-digestion with agricultural residues (i.e., cucumber, tomato, eggplant, and pepper), can enhance methane production of 380.50 mL/g VS and optimize resource utilization an initial pH of 7.3, organic load of 18.8 g VS/L, and residues ratio of 3.9:1 [11]. Furthermore, advancements in microbial fuel cell technologies are paving the way for more efficient bio-electrochemical systems that can directly convert food waste into electricity, thereby offering a dual benefit of waste treatment and energy generation. A recent study conducted by El Salamony et al. [12] has reported that the comparison results between anaerobic digestion and bio-electrochemical technologies for producing electricity using chicken feather waste can produce hydrogen 0.85 mmol/day/L and 7.5 mmol/day/L, respectively. This study also investigated the important of using hydrolysis pretreatment to enhance microbial activity to produce hydrogen because it breaks down complex organic materials into simpler compounds, making them more accessible for microbial communities.

This review aims to provide a novel contribution by focusing on the recent advances and applications of these emerging technologies in the conversion of food waste to bioenergy. Unlike previous reviews that primarily focus on traditional methods, this paper presents a comprehensive analysis of innovative approaches and their synergy with conventional techniques for optimizing energy recovery and waste reduction. This review also provides a comprehensive overview of the principles, processes, and benefits associated with each technology, as well as the current state of research and potential future directions. Crucially, the matching and screening of food waste types for energy conversion plays a vital role in optimizing resource recovery and maximizing energy output. This approach (i.e., matching and screening) enhances efficiency and sustainability in energy generation also increases the potential for scaling up production. By exploring the latest developments in the field of bioenergy and waste management, this review highlights the significant potential of food waste as a valuable resource for bioenergy production and contribute to the ongoing efforts to achieve sustainable waste management and energy security.

2. Type of Food Waste: Matching, Screening and Assessing Energy Potential

The matching and screening of food waste types for energy conversion is crucial for optimizing resource recovery and maximizing energy output. Different food waste types possess unique compositions that influence their suitability for various energy production processes, as shown in Table 1. By understanding the specific characteristics of these waste types, we can effectively match food waste to appropriate conversion technologies, ensuring higher efficiency and sustainability in energy generation.

Table 1. Classification of food waste compounds and prospect value-add products from food waste to enhance bioenergy production.

Waste Types	Sources	Products	Methods	Target Compounds	Limitations
High sugar and proteins	Fruits, vegetables, dairy products, meat, fish	Biomethane, Bio-oil	Microbial Fuel Cells (MFCs), Hydrothermal Liquefaction (HTL)	• Lipids • Proteins	• Potential for microbial contamination • Requires precise control over environmental conditions
Starch and fiber waste	Rice, peels, stalks, grains, bakery products	Bioethanol, electricity	Synthetic Biology, Metabolic Engineering, MFCs	• Complex carbohydrates (starch, cellulose, hemicellulose) • Simple sugars (glucose, fructose, sucrose) • Starch	• High pretreatment costs • Slower degradation rates • May require significant energy inputs
Oily and high energy waste	Used oil, grease, processed foods	Biodiesel, Liquid Hydrocarbons	Transesterification, Gasification with Fischer-Tropsch Synthesis	• Lipids • Fatty acids	• Odor management challenges • Requires efficient containment and handling systems
High moisture and nutrient	Soups, sauces, beverages, coffee grounds	Hydrogen, Syngas	Supercritical Water Gasification (SCWG)	• Proteins • Moisture content	• High processing costs • Requires careful handling to prevent emissions • Complex operation

2.1. High Sugar and Proteins

High sugar and protein wastes, such as fruit, vegetable scraps and dairy byproducts, are highly suitable for bioenergy production through microbial fuel cells (MFCs) and anaerobic digestion. These substrates are matched to energy production processes because of their rich organic content, which facilitates significant biomethane generation. This process involves the breakdown of organic material by microorganisms in an oxygen-free environment, resulting in the generation of biomethane, primarily composed of methane (CH_4) and carbon dioxide (CO_2). Studies have demonstrated that high sugar and protein waste can yield significant amounts of biogas, for instance by Jiang et al. [13] has reported the maximum yield of biomethane yield of 269.9 mL/g TCOD from anaerobic co-digestion of mixture food waste (i.e., apples, cabbage, potatoes, and bananas). High sugar and protein waste ferments rapidly, yielding substantial biomethane. However, the efficiency of this process is contingent upon optimal conditions (i.e., pH, temperature, and the carbon-to-nitrogen (C/N) ratio), which must be managed to sustainable microbial activity. A previous study conducted by Xue et al. [14], highlighted that maintaining a C/N ratio of around 25:1 significantly improved biogas production of 12,322 mL. Pre-treatment methods, such as mechanical shredding or thermal hydrolysis, can enhance the biodegradability of these substrates by breaking down complex structures, thereby increasing accessibility for microbial degradation. For instance, thermal hydrolysis has been shown to increase methane yields of 197 mL/g COD compared to untreated waste of 186 mL/g COD [15]. Overall, the conversion of high sugar and protein waste into biomethane represents a sustainable approach to waste management while contributing to renewable energy generation.

2.2. Starch and Fiber Waste

Starch and fiber waste, such as rice, peels, stalks, grains, and bakery also present a promising avenue for bioenergy production, primarily through fermentation, synthetic biology and metabolic engineering methods for bioethanol production. This food waste, often discarded or underutilized, can be converted into biofuel through fermentation processes, thereby addressing both energy needs and environmental concerns [16,17]. These compounds from food waste can be effectively matched to fermentation technologies, addressing energy needs while minimizing environmental impacts. While the yield of bioethanol from starch sources is often higher than that from fibrous materials, the latter can be converted through enzymatic hydrolysis followed by fermentation. Compared to high sugar and protein waste, the conversion of starch and fiber requires more complex pretreatment processes to break down cellulose and hemicellulose into fermentable sugars. The conversion process begins with enzymatic hydrolysis, where starch is broken down into fermentable sugars, primarily glucose, using specific enzymes such as α-amylase and glucoamylase [18]. Following hydrolysis, the glucose is fermented by yeast strains, typically *Saccharomyces cerevisiae*, to produce bioethanol and carbon dioxide. The fermentation conditions, including temperature, pH, and fermentation time, play a crucial role in optimizing bioethanol yield. Furthermore, advances in synthetic biology and metabolic engineering can enhance yeast strains performance, allowing them to utilize a broader range of substrates and improve ethanol tolerance as explained in Section 3.

2.3. Oily and High Energy Content Waste

Oily and high-energy content waste, such as used cooking oil and fatty food scraps, can be converted into biodiesel and liquid hydrocarbons through transesterification and gasification coupled with Fischer-Tropsch synthesis processes. These waste streams are characterized by their high energy density, which makes them an attractive feedstock for biofuel production. By converting these wastes into liquid hydrocarbons, we can address the challenges of waste disposal while contributing to the generation of renewable energy. Recent studies support the efficacy of these conversion methods. For instance, gasification coupled with Fischer-Tropsch synthesis is highly effective in transforming oily waste into syngas, which can then be catalytically converted into high-quality liquid hydrocarbons [19]. Their research shows that this approach not only enhances the yield of liquid hydrocarbons but also improves the overall energy efficiency compared to traditional methods Eyberg et al. [20]. In contrast, Mailaram et al. [21] highlight the advantages of transesterification for biodiesel production from fatty waste. Their study finds that while transesterification is well-suited for producing biodiesel from triglycerides, it may not be as effective in generating high-quality liquid hydrocarbons compared to gasification and Fischer-Tropsch synthesis. Moreover, advancements in biodiesel production through hydrotreating have shown promise, especially when using catalysts such as nickel (Ni), cobalt (Co), palladium (Pd), platinum (Pt), ruthenium (Ru), and Iron (Fe). A recent study by Kopli et al. [22] has reported that the green diesel produced through hydrotreating of cooking oil using a $60Ni/Al_2O_3$ catalyst achieved specific properties, including a density of 766.77 ± 0.679 kg/m^3, a viscosity of 66.13 ± 0.249 mm^2/s, and a flash point of 2.92 ± 0.011 °C, making it a viable alternative to conventional diesel. To maximize the efficiency of liquid hydrocarbon production, effective pre-treatment of feedstocks, including filtration and the removal of contaminants, is essential, as these steps ensure cleaner inputs and reduce the risk of catalyst deactivation.

2.4. Higher Moisture and Nutrient Waste

Higher moisture and nutrient-rich wastes, such as agricultural residues, food processing byproducts, and wastewater, are ideal feedstocks for hydrogen and syngas production through supercritical water gasification (SCWG). The high moisture content facilitates the use of supercritical water, which acts as a solvent and reactant, enabling efficient solubilization and breakdown of organic materials without the need for extensive drying. This process yields hydrogen, carbon monoxide, and other valuable gases, which can be utilized as renewable energy sources or as feedstocks for chemical synthesis. Based on the research conducted by Ferreira-Pinto et al. [23] has demonstrated that SCWG is more efficient with biomass concentrations below 10 wt.%, making high-moisture agricultural waste a viable feedstock for the process. They found that the presence of water in SCWG enhances the solubility and reactivity of organic compounds, leading to more efficient gasification processes. Similarly, research by Molino et al. [24] emphasizes the effectiveness of SCWG in agricultural residues with higher moisture content of 95.40 ± 0.5% *w*/*w* can enhance gas yields between hydrogen and carbon dioxide (40 vol.%) and methane (14 vol.%). However, the presence of inhibitory compounds in higher moisture wastes can pose challenges for the SCWG process. These compounds, which may include phenolic compounds, nitrogenous substances, and other contaminants, can inhibit enzymatic activity and gasification efficiency. As noted by Adar et al. [25], these inhibitors can adversely affect the SCWG process by reducing the overall efficiency and gas yield. To address these issues, implementing pre-treatment methods, such as physical or chemical treatments, may be necessary to reduce these inhibitors and enhance the overall efficiency of the SCWG process. Pre-treatment strategies, as discussed by Ramos et al. [26], can also improve the accessibility of organic materials to supercritical water, thereby increasing the yield of hydrogen and syngas. Acid and alkaline treatments reduce inhibitory compounds such as lignin and tar precursors by breaking down complex structures and removing impurities. The use of alkali is particularly effective for feedstocks with high lignin content, as it helps break down lignin and improve gasification performance [27]. Moreover, acid pretreatment are established reagents that facilitate the release of fermentable sugars by breaking glycosidic bonds in lignocellulose and dissolving cellulose and hemicellulose, with a lesser effect on lignin [27]. This combination of treatments enhances thermal decomposition and promotes higher conversion rates of biomass into hydrogen and syngas.

3. Food Waste to Energy Technologies

Conversion of wasted food to biofuels is one of the best options to divert from landfills. Direct processing of food waste typically focuses on utilizing the solid and liquid form of waste due to practical and operational considerations. However, this processing can result in the generation of new waste, such as sludge, which needs to be managed effectively to minimize environmental impact and maximize resource recovery. Food waste contains organic matter that can be effectively processed through various technologies such as anaerobic digestion, fermentation, pyrolysis, and gasification. However, this process is a traditional technique for converting food waste into biofuels through direct processing [28]. Therefore, this section will explore more as recent technologies, such as hydrothermal liquefaction (HTL), hydrothermal carbonization (HTC), hydrothermal gasification (HTG), gasification coupled with Fischer-Tropsch synthesis, and bioelectrochemical conversion to methane from food waste. Figure 1 illustrates the direct conversion technologies of turning solid and liquid food wastes to biofuels, and the recent studies are presented in Table 2.

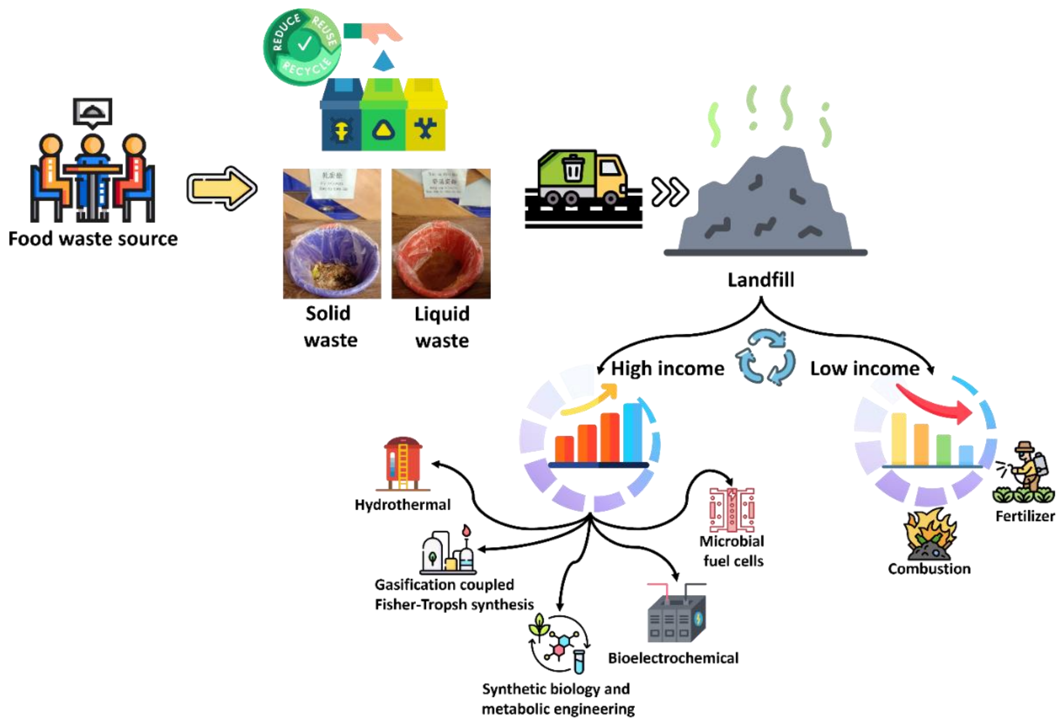

Figure 1. Conversion strategies of food waste to biofuels with recent advance, such as hydrothermal, gasification coupled Fisher-Tropsh synthesis, bioelectrochemical, microbial fuel cell, and synthetic biology and metabolic engineering.

Table 2. Recent studies of the direct conversion of food waste into biofuels.

Food Waste (Co-Substrate & Concentration)	Pretreatment	Temperature (°C)	Pressure (MPa)	Catalyst	Reaction Time	Reactor Type	Biofuel Production	Limitation	References
Hydrothermal liquification (HTL)									
Pineapple, watermelon, banana peel	Alkaline and hydrothermal pretreatment	300–350	-	K_2CO_3 (10 wt.%)	0–60 min	-	Bio-oil: 56.55%	High transportation cost	[29]
Food waste	Mechanical pretreatment	-	-	-	-	Pilot scale	Bio-oil: 29.5 wt.%	Economic performance	[29]
Food waste	Mechanical pretreatment	-	-	-	-	Lab scale	Bio-oil: 21.9 wt.%	Economic performance	[29]
Food waste	Mechanical pretreatment	400	22	-	-	-	Biocrude: 73%	Economic evaluation and biochemical composition	[30]
Canned green beans, baked beans, potato salad, canned chicken, shredded parmesan cheese (2-20 wt%)	Mixing	200–600	10.2–35.7	-	1–33 min	-	Biocrude: 30 wt.%	Modified kinetic study	[31]
Hydrothermal carbonification (HTC)									
150 g Food waste	-	105	-	-	-	Autoclave	Hydrogen: 69.8%, 57–59 mol H_2/kg hydrochar	Economic evaluation and product improvement	[29]
10 g food waste and 100 mL distilled water	-	210–270	-	-	60–90 min	200 mL Hastelloy batch reactor	HHV hydrochar: 46.92–51.82%	Application hydrochar	[32]
Hydrothermal gasification (HTG)									
Food waste	$NaHCO_3$	300–400	20–25	-	-	-	Hydrogen: 43%	Improve water-gas shift reaction	[33]
Rice, cabbage, pork	Mechanical pretreatment	800	-	-	15 min	-	Hydrogen: 29.5%	Need torrefaction improvement	[34]
Gasification coupled with Fischer-Tropsch synthesis									
Biomass	-	450 (Gasification) / 210 (FT Reactor)	0.2 (Gasification) / 30 (FT Reactor)	-	-	Gasifier + FT Reactor	Syngas: 56.3%	Reduce cost in gasification and FT process	[35]
Food waste (30% vegetables, 70% cereals)	-	550	-	-	7 sec	Microwave	Bio-oil: 40–52%, Biochar: 30–46%, Syngas: 10–30%	Economic evaluation	[36]
Bio-electrochemical									
Food waste	Mechanical pretreatment (blender)	-	-	-	-	Anode (2.2 cm diameter, 8 cm length), Ti/RuO_2 cathode	Methane: 44.3 mL/L reactor	Maximize energy recovery	[37]
Food waste	Electrical pulverization	-	-	-	-	Single chamber, 65.94 cm^2 electrode surface	Syngas to power: 41.58 mW/m	Electron transport issues	[38]
Organic waste	-	-	-	-	-	Anode & cathode (4 × 4 cm carbon cloth, stainless steel), 35 ± 2°C reactor	Ethanol: 0.31 kg/m^2/day	Power consumption & cost evaluation	[39]
Supercritical water gasification (SCWG)									
Food waste	-	400–450	-	-	-	250 mL batch reactor	Hydrogen: 7.89 mol/kg	Scale-up production	[40]
Food waste (5–15 wt.%)	Mechanical pretreatment	550–850	-	-	-	Micro quartz batch reactor	Hydrogen: 55.3 mol/kg	Economic evaluation	[41]

3.1. Food Waste to Fuels and Electricity through Hydrothermal Conversion

Hydrothermal conversion processes are highly effective for converting food waste to fuels and chemicals at high temperature and pressure. This method is particularly advantageous for processing wet biomass, like food waste, because it eliminates the need for energy-intensive drying processes. There are three main types of hydrothermal conversion processes: Hydrothermal Liquefaction (HTL), Hydrothermal Carbonization (HTC), and Hydrothermal Gasification (HTG). These processes can produce a variety of products, including bio-oil, biochar, and syngas, which can be further refined into fuels or used directly to generate electricity.

3.1.1. Hydrothermal Liquefaction (HTL)

HTL involves converting wet biomass, including solid and liquid food waste, into liquid biofuels under high temperature (i.e., 250 to 400 °C) and pressure (i.e., 10 to 25 MPa) in the presence of a solvent. This process yields bio-oil, which can be further refined into transportation fuels or specialty chemicals. HTL is particularly advantageous as it can handle a wide range of feedstocks with higher moisture content and does not require drying, thus reducing preprocessing costs and energy consumption [42,43]. HTL can achieve high bio-oil yields from food waste through direct processing due to its ability to efficiently convert complex organic materials into liquid fuels. Studies by researchers by Bayat et al. [44] have demonstrated that the highest bio-crude oil yield of 27.5 wt.%, was achieved at the lowest temperature of 240 °C with a reaction time of 30 min. This research proves that HTL can be carried out at a temperature of 250 °C for a longer time. HTL offers a promising pathway for converting food waste into valuable biofuels due to its high conversion efficiency and versatility in handling feedstock variability [45]. For instance, previous study by Posmanik et al. [46] highlights advancements in catalyst technology, such as acid and alkaline can produce higher heating value (HHV) biocrude of 32.5 ± 0.7 MJ/kg and 35.4 ± 1.0 MJ/kg, respectively, as compare without catalyst can produce HHV biocrude of 34.8 ± 1.3 MJ/kg. These developments underscore HTL potential as a viable technology for sustainable biofuel production from food waste.

3.1.2. Hydrothermal Carbonization (HTC)

This technology involves the conversion of organic materials in food waste into a mixture of hydrogen, carbon monoxide, and methane gases under temperatures of 200 to 600 °C and pressures of 5 to 30 MPa with water as a solvent. This process can be integrated with combined heat and power systems to produce electricity and heat, in addition to gaseous biofuels. Compared to conventional gasification methods, HTC operates at lower temperatures, reducing tar formation and improving overall efficiency. A recent study conducted by Yan et al. [47] has reported that the HTC under 275 °C for 60 min can produce hydrochar with calorific value of 22.68 MJ/kg in the food waste material. This study also reported the highest hydrogen rich syngas production of 1151.26 mmol·L at 480 °C and 45 min with 5 wt.% KOH. HTC presents a sustainable route for converting food waste into gaseous biofuels, contributing to renewable energy goals and waste management strategies.

3.1.3. Hydrothermal Gasification (HTG) or Supercritical Water Gasification (SCWG) for Fuels

HTG is a thermochemical process that converts biomass into a synthesis gas (syngas) comprising hydrogen, carbon monoxide, methane, and other trace gases under high temperature (400–800 °C) and pressure (10–25 MPa) conditions in the presence of water and a gasification catalyst [48]. Unlike traditional gasification processes that use dry biomass, HTG operates with wet biomass feedstocks (i.e., solid and liquid of food waste), making it suitable for treating high-moisture organic wastes such as food waste and sewage sludge [49,50]. Numerous studies have explored the hydrothermal gasification of pre-treated kitchen waste as feedstock. However, research on the hydrothermal gasification of raw kitchen waste remains limited. The effectiveness of hydrothermal gasification for kitchen waste is highly influenced by its inherent properties, including elemental composition, heating value, ash content, moisture content, and volatile solid content [51,52]. For instance, Rajagopal et al. [53] has comparison study for HTG (280–420 °C) and HTL (280–360 °C) at pressure 5 MPa for 60 min can produce hydrogen yield of 39 wt.% and 26 wt.%, respectively, in household mixed waste. This result proves the HTG involves the partial oxidation of biomass, where the organic matter is broken down into gaseous components that can be used for heat and power generation, hydrogen production, or further synthesis of liquid fuels and chemicals.

Other technologies of SCWG are advanced technology for converting organic waste into syngas hydrogen, carbon monoxide, and carbon dioxide by utilizing supercritical water. At temperatures above 374 °C and pressures exceeding 22 MPa, water enters a supercritical state, acting as both a solvent and reactant. This allows for the efficient breakdown of organic materials into simpler gaseous products. The primary advantage of SCWG over traditional waste treatment methods, such as incineration and anaerobic digestion, lies in its ability to achieve high efficiency in waste conversion. SCWG can produce hydrogen-rich syngas that is not only a renewable energy source but also a versatile feedstock for producing fuels and chemicals. For instance, study by Cao et al. [54] has reported that the SCWG at 650 °C can produce hydrogen of 38.29 mol/kg in 7 wt.% food waste and catalyst loading of 14 wt.% K_2CO_3. This study suggests that high temperature and high catalyst loading can enhance the hydrogen production in SCWG. In contrast to incineration, which releases harmful emissions and only recovers energy through heat, SCWG significantly minimizes harmful pollutants while maximizing energy recovery. Additionally, SCWG can process a wide range of organic feedstocks, including low-quality waste and diverse feedstocks that would otherwise be challenging to convert using traditional methods. This versatility enhances the potential for integrating SCWG into existing waste management systems, promoting sustainable waste-to-energy solutions that align with circular economy principles.

3.2. Gasification Coupled Fischer-Tropsch Synthesis to Convert Food Waste to Liquid Hydrocarbons

Recent technology, gasification coupled with Fischer-Tropsch (FT) synthesis involves converting syngas (synthesis gas) produced from gasification of food waste into liquid hydrocarbons such as diesel and jet fuels using FT catalysts. This process allows us to produce high-quality transportation fuels from food waste-derived syngas. FT synthesis from food waste-derived syngas offers higher selectivity towards liquid hydrocarbons compared to traditional gas-to-liquid processes. In fact, this is a new technology for application in food waste biomass into fuels. Gasification coupled with FT synthesis represents a promising approach for converting food waste into high-quality liquid fuels, addressing both energy security and environmental sustainability. Studies by Yang et al. [55] emphasize the role of catalyst innovation in improving product selectivity and process economics, supporting FT synthesis as a viable technology for biofuel production from food waste. Mitigates landfill methane emissions by converting waste into useful products. However, energy-intensive processes and emissions from high-temperature operations impact environmental sustainability [55].

3.3. Bioelectrochemical Conversion of Food Waste to Biomethane

Recently, methane production can produce with bioelectrochemical conversion involves using microbial electrochemical systems (MES) to convert organic compounds in food waste into methane gas through anaerobic digestion processes enhanced by electrochemical reactions. This method integrates microbial metabolism with electricity generation to produce renewable methane biofuels. Bioelectrochemical conversion offers higher methane yields and process efficiency compared to traditional anaerobic digestion methods. At the heart of this technology are specialized electrodes: the anode, typically constructed from carbon-based materials such as carbon brushes, and the cathode, often composed of titanium coated with ruthenium oxide (Ti/RuO_2) or graphite felt [56]. These electrodes play pivotal roles in facilitating electron transfer and optimizing the conversion of organic compounds into methane gas. In the bioelectrochemical system, organic matter undergoes microbial oxidation at the anode, where bacteria break down complex molecules and release electrons as byproducts. These electrons are then transported through an external circuit to the cathode, where they participate in electrochemical reactions that reduce protons and carbon dioxide to methane [57]. This dual process of microbial metabolism and electrochemical enhancement not only increases methane yields per unit of organic substrate but also improves overall process efficiency [58]. Compared to traditional anaerobic digestion methods, bioelectrochemical conversion offers significant advantages in terms of methane production rates and energy recovery. Moreover, by harnessing microbial activity to generate renewable methane biofuels alongside electricity, this technology holds promise for addressing challenges in waste management, reducing greenhouse gas emissions, and advancing the transition towards a circular economy. A previous study by Park et al. [59] has reached the methane production of 133 ± 0.02 mL-CH_4/g-$VS_{residual}$ through bioelectrochemical process as compared to anaerobic digestion process only produce the methane of 125 ± 0.03 mL-CH_4/g-$VS_{residual}$. Other study by Ding et al. [60] has reported that food waste leachate was treated with bioelectrochemical can produce CH_4 of 526.7 mL/gVS in electrode area of 25.2 cm^2/L. Bioelectrochemical conversion presents a sustainable pathway for producing methane biofuels from food waste, leveraging synergies between microbial metabolism and electrochemical processes. Ongoing research and development efforts focus on optimizing electrode materials, refining operational parameters, and scaling up bioelectrochemical systems to maximize their economic viability and applicability across diverse industrial and environmental settings.

3.4. Microbial Fuel Cells (MFCs) for Electricity Generation from Food Waste

Microbial fuel cells (MFCs) harness the power of microorganisms to generate electricity by oxidizing organic substances. In MFCs, microorganisms at the anode break down organic matter, producing electrons and protons.

The electrons travel through an external circuit to the cathode, where they participate in reduction reactions. This process not only produces electricity but also helps in treating wastewater, making MFCs a dual-purpose technology. The anode typically consists of materials like carbon-based electrodes, which are conducive to microbial activity, while the cathode facilitates the necessary reduction reactions. MFCs offer a renewable and environmentally friendly energy source with minimal impact, addressing both energy generation and waste management challenges [61]. The advantages of MFCs over traditional energy generation methods, such as anaerobic digestion, are notable. Previous study conducted by Xin et al. [62] has reported that the comparison technology between anaerobic digestion and MFCs can produce electricity from food waste of 167.5 and 192.5 million kWh, respectively. This higher energy output is attributed to MFCs' ability to directly convert organic substrates into electricity without the intermediate steps required in anaerobic digestion. Furthermore, MFCs operate under mild conditions, which reduces the energy input for operation and minimizes greenhouse gas emissions. The carbon-based electrodes used in MFCs not only facilitate microbial activity but also enhance the overall efficiency of the electron transfer process, making them more sustainable. MFCs represent a promising pathway for renewable energy generation, enabling a circular economy approach by converting waste into valuable energy.

3.5. Synthetic Biology and Metabolic Engineering for Bioethanol Production

Synthetic biology and metabolic engineering are pivotal in optimizing bioethanol production from various feedstocks (i.e., food waste). Synthetic biology and metabolic engineering are also emerging as effective methods for converting organic matter, such as high-sugar and starch-rich food waste into bioenergy, as highlighted in Table 1. Synthetic biology involves designing and constructing new biological systems to enhance the production of bioethanol, while metabolic engineering focuses on modifying microorganisms to improve their fermentation capabilities. The advantages of these modern techniques over traditional fermentation processes are significant. Traditional bioethanol production often relies on first-generation feedstocks, such as sugarcane or corn, which can contribute to food competition and land use issues. In contrast, synthetic biology enables the utilization of lignocellulosic biomass and waste materials, thus promoting sustainable practices without compromising food supplies. Recent studies have demonstrated the effectiveness of these approaches. For instance, engineered yeast strains developed through metabolic engineering have been shown to increase ethanol yields by up to 114.71 g/L using *S. cerevisiae* MC15 with genetic of phosphate response signal (PHO4) [63]. Additionally, advancements in metabolic engineering allow for the development of engineered yeast or bacteria that can ferment a broader range of sugars, including those derived from non-traditional sources, leading to higher ethanol yields. Furthermore, these technologies enable the optimization of metabolic pathways, enhancing the efficiency of converting sugars into ethanol. A previously study by Semkiv et al. [64] has investigated co-expression studies of a gene encoding a molecular chaperone protein (SSB1) from *S. cerevisiae*, a gene of ATP-diphosphohydrolases obtained from *E. coli*, and a galactose-induction approach led to a significant increase in ethanol production of 17% and 28%. By employing synthetic biology tools, researchers can create microorganisms that better tolerate high ethanol concentrations, increasing overall process efficiency. As a result, the integration of synthetic biology and metabolic engineering in bioethanol production supports the development of renewable energy sources, reduces reliance on fossil fuels, and contributes to a more sustainable circular economy.

4. Future Prospect and Challenges for Scale Up of Food Waste to Bioenergy to Create Sustainable Process and Net-Zero Scenario

The transition from laboratory-scale experiments to industrial-scale applications is a critical step in realizing the potential of food waste to bioenergy technologies. Scaling up involves addressing various technical, economic, and regulatory challenges to ensure that these processes are not only feasible but also economically viable and environmentally sustainable on a larger scale. Effective feedstock management is essential for the successful scale-up of food waste to bioenergy processes. This involves the collection, transportation, and preprocessing of food waste to ensure a consistent and reliable supply of feedstock to the conversion facilities. One of the main challenges in feedstock management is the heterogeneous nature of food waste, which can vary widely in composition, moisture content, and contamination levels. Developing standardized methods for sorting, preprocessing, and storing food waste can help address these challenges and improve the efficiency and performance of bioenergy conversion processes. For instance, Mechanical pre-treatment such as blending and pulverization can improve the hydrolysis rate of food waste by reducing the particle size as well as converting solids into liquids or sludges [65,66]. In fact, the process of milling refers to the mechanical grinding or pulverizing of raw materials to achieve a specific particle size (<2 mm) [67]. A recent study conducted by Gu et al. [68] has reported the particle size of food waste that was pre-treated with ball mill can be reduced to 176 μm and was converted into liquid form. On the other hand, crushing method is a simpler process where the particle size of the food waste can be reduced up to <3 mm [69]. It was found that the particle size of food waste subjected to crushing process (i.e., hammer mill and chopper) can be reduced to less than 12 mm and 19.1 mm, respectively [70,71].

Optimizing the conversion processes is crucial for maximizing the yield and quality of biofuels produced from food waste. This involves fine-tuning various process parameters, such as temperature, pressure, residence time, and catalyst concentration, to achieve optimal performance. Advanced process control systems and real-time monitoring technologies can help in precisely controlling these parameters and ensuring stable and efficient operation of the conversion processes. The integration of computational modeling and simulation tools can also aid in process optimization by providing insights into the reaction mechanisms and kinetics, allowing for the prediction and control of process performance. Additionally, pilot-scale testing and demonstration projects can help validate the optimized process conditions and identify potential operational issues that may arise during scale-up. Integrating food waste to bioenergy technologies with existing waste management and energy infrastructure can enhance their feasibility and cost-effectiveness. This involves leveraging existing collection and transportation networks, waste treatment facilities, and energy distribution systems to streamline the implementation of these technologies on a larger scale. For instance, anaerobic digestion facilities that are already processing organic waste can be retrofitted or expanded to include advanced bioelectrochemical systems for enhanced methane production [72]. Similarly, waste-to-energy plants can incorporate gasification coupled with Fischer-Tropsch synthesis units to convert syngas into liquid biofuels [73].

To advance the scaling of food waste to bioenergy technologies, future research should focus on several key areas: developing standardized protocols for sorting and preprocessing various types of food waste to enhance efficiency, investigating novel pretreatment techniques to improve hydrolysis and fermentability, and optimizing conversion parameters for existing technologies to boost yields. Additionally, exploring the integration of bioenergy production with renewable energy systems can enhance sustainability, while conducting pilot-scale studies can validate laboratory findings and assess operational challenges. Economic viability assessments should also be conducted to evaluate the cost-effectiveness of scaling up food waste to bioenergy technologies, along with lifecycle assessments to quantify environmental impacts. By addressing these areas, future research can significantly contribute to the effective scaling and implementation of food waste to bioenergy technologies, promoting a more sustainable and circular economy.

5. Conclusion

Food waste to bioenergy represents a promising solution to address both waste management challenges and the growing demand for sustainable energy sources. By focusing on the effective matching and screening of food waste types for energy conversion, along with optimizing preprocessing and conversion technologies, we can unlock the full potential of food waste as a valuable resource. This review highlights the need for continued research and innovation in this field, emphasizing the importance of integrating bioenergy systems with existing infrastructure and renewable energy sources. Ultimately, advancing food waste to bioenergy technologies can significantly contribute to sustainable waste management, energy security, and the transition to a circular economy. Addressing the heterogeneity of food waste remains a significant challenge in scaling up bioenergy production. Developing standardized methods for feedstock management, including preprocessing and sorting, is essential for ensuring a reliable supply of high-quality materials for conversion processes. Furthermore, integrating these bioenergy systems with existing waste management infrastructure can streamline implementation and reduce costs, facilitating broader adoption across various sectors. Future research should prioritize the optimization of conversion technologies and the exploration of integrated systems that combine multiple methods to maximize resource utilization. Additionally, examining the socio-economic implications of food waste-to-bioenergy initiatives can provide valuable insights for policymakers and stakeholders. By fostering collaborative efforts and supportive policies, it is possible to accelerate the transition towards sustainable waste management practices that leverage food waste as a significant energy resource.

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