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Review

Advances in Technologies for the Treatment of and Resource Recovery from Organic Wastes: A Review

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Abstract

Effective management of organic wastes is essential for green and low-carbon development. Conventional technologies, including incineration, pyrolysis, hydrothermal carbonization (HTC), gasification, anaerobic digestion (AD), and composting, have supported waste reduction and basic resource recovery, but they remain limited in high-efficiency conversion and high-value utilization. This review comparatively evaluates these conventional routes together with advanced and intensified technologies, including microwave-assisted pyrolysis (MAP), plasma treatment, supercritical water gasification (SCWG), and flash joule heating (FJH), with emphasis on suitable feedstocks, performance characteristics, application boundaries, and integration potential. In general, wastes with high moisture content are more suitable for HTC, AD, and SCWG, whereas relatively dry wastes and wastes with high carbon content are more suitable for pyrolysis, gasification, plasma treatment, and FJH upgrading. The review also discusses representative integrated pathways, such as HTC-SCWG, pyrolysis and plasma coupling, AD and gasification coupling, and pyrolysis and FJH coupling, which may improve carbon conversion, broaden product portfolios, and reduce residual pollutants. However, large-scale implementation is still constrained by feedstock heterogeneity, heat and mass transfer limitations, catalyst deactivation, reactor corrosion, and system cost. Overall, no single technology is universally optimal; technology selection should depend on feedstock properties, moisture content, and target products.

Keywords: anaerobic digestion; plasma gasification; supercritical water gasification; thermochemical conversion; waste treatment

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1. Introduction

According to the United Nations Environment Programme, around 11.2 billion tons of solid waste are generated globally each year [1]. The generation, composition, and management priorities of organic waste vary considerably across regions, including China, the European Union, the United States, and many developing countries. The dominant waste streams and policy drivers differ by region. For example, the European Union has increasingly emphasized separate collection of bio-waste and circular bioeconomy strategies, whereas the United States faces large flows of municipal solid waste and wasted

food, and many developing countries continue to experience rapid waste growth together with insufficient collection and treatment infrastructure [2].

These wastes act both as environmental burdens and as potential resources [3]. Through thermochemical conversion, biological conversion, and related pathways, organic waste can be transformed into energy, fertilizers, chemicals, and other value-added products, thereby promoting circular resource use, improving resource efficiency, and reducing environmental pollution [4]. The current mainstream treatment routes for organic waste include landfilling, incineration, composting, and AD. These technologies have undergone long-term development and now play important roles in waste reduction and basic resource recovery [5]. However, landfilling and incineration may generate greenhouse gases and harmful by-products such as persistent organic pollutants, acid gases, and heavy metals, whereas biological conversion routes such as composting and AD are often constrained by long processing times, relatively low conversion efficiency, and residual contaminants [6].

In recent years, a range of advanced and intensified technologies focusing on energy conversion and material recycling have attracted increasing attention. Among them, MAP has been reported to improve heating uniformity and, under suitable conditions, enhance product selectivity relative to conventional pyrolysis [7]. FJH enables the ultrafast upgrading of selected precursors with high carbon content into highly crystalline carbon materials [8]. Plasma treatment can promote the cracking of complex organics and the destruction of persistent pollutants, although its performance depends strongly on energy input and reactor configuration. SCWG is particularly suitable for feedstocks with high moisture content because it avoids the drying step required by conventional gasification [9]. Collectively, these advanced routes provide additional options for the valorization of organic waste, although their advantages are highly technology-specific and depend on feedstock properties, process integration, and scale-up conditions.

Unlike previous reviews that focus on individual technologies, this work provides (i) a comparative evaluation across conventional and advanced routes, (ii) a feedstock-oriented analysis linking waste characteristics to optimal technologies, and (iii) a critical assessment of integration pathways and scalability constraints.

2. Current Status of Organic Waste Generation and Treatment

Solid waste can be categorized according to its source into several types, including household waste, institutional waste, agricultural waste, biomedical waste, municipal waste, and industrial waste [10].

Municipal solid waste (MSW) refers to the waste generated by households, businesses, and institutions within a defined geographic area. Globally, approximately 2 billion tons of MSW are produced each year, and this amount is projected to reach 3.5 billion tons by 2050 [11–13]. According to the China Urban and Rural Construction Statistical Yearbook, in 2023, the total volume of collected and transported solid waste in China reached 350 million tons, of which approximately 254 million tons originated from urban areas. MSW generation and management show marked regional differences. For example, substantial per capita disparities have been reported between developed and developing countries, and rapid increases in MSW generation have been observed in countries such as China, India, and Indonesia. China has been reported as the world's largest MSW generator, while the United States also produces a comparably large municipal waste stream, and the European Union has increasingly emphasized waste sorting, recycling, and bio-waste diversion [14]. If not properly managed, MSW can lead to soil, water, and air pollution, posing serious risks to human health and ecological stability. At the same time, its biodegradable fraction is rich in proteins, carbohydrates, lipids, and plant nutrients such as nitrogen, phosphorus,

and potassium, making it a potentially valuable feedstock for energy recovery and resource utilization [15].

Agricultural solid waste (ASW) constitutes a major component of the global waste stream and is mainly generated from crop cultivation, livestock and poultry farming, agricultural product processing, and forestry operations [16]. It includes crop residues as well as livestock-derived wastes such as manure, slurry, carcasses, and straw. Owing to the diversity of these feedstocks, the composition of ASW varies substantially, although lignocellulosic components such as cellulose, hemicellulose, and lignin are dominant in many plant-derived residues [17]. Many ASW streams are also rich in organic matter and nutrients, which makes them suitable for biogas generation, biofertilizer production, composting, feed conversion, and material recycling [18–21].

Industrial solid waste (ISW) is generated before, during, or after manufacturing processes, or as by-products from various industrial sectors [22]. It is typically characterized by complex composition, large output, and relatively low recycling efficiency. China, as the world's largest industrial producer, generates about 4 billion tons of ISW annually [23]. Large quantities of non-hazardous industrial waste are also generated in developed economies such as the United States. Owing to the diversity of industrial wastes and their potential environmental risks when improperly stored or disposed of, traditional management routes have mainly included landfilling, incineration, physical separation, and selected biological treatments for biodegradable industrial residues [24–26]. Nevertheless, many ISW streams still have considerable potential for valorization. For instance, waste plastics and end-of-life tires are suitable for energy and material recovery because of their high carbon content and calorific value, whereas waste textiles can be sorted, defibered, composted, or pyrolyzed to produce fillers, compost-like products, or biochar [27].

Overall, the composition and physicochemical characteristics of different types of solid waste determine their suitable treatment and resource utilization pathways, highlighting the importance of adopting diversified and targeted technologies to achieve efficient waste management and sustainable resource recovery.

3. Conventional and Thermochemical Treatment Technologies

The main conventional methods of organic waste treatment are incineration, pyrolysis, HTC, gasification, AD, and aerobic composting. To facilitate an overall understanding before the detailed discussion of each route, Figure 1 presents a schematic comparison of selected mainstream organic waste treatment technologies, including their underlying principles and representative process structures. Table 1 further summarizes the main characteristics of these technologies, which are discussed in detail below.

3.1. Incineration

Incineration technologies for municipal solid waste treatment are relatively mature and have been widely applied in engineering practice [28]. In practical engineering, the net electrical efficiency of waste incineration power generation is typically about 14–28%. Under combined heat and power (CHP) mode, the total system efficiency can further increase to 60–80% when well-established district heating networks are available [29]. Incineration techniques are evolving toward cleaner, more efficient, and smarter approaches [30]. The core advantages of incineration lie in its high technological maturity, remarkable waste volume reduction effect, and clear pathway for thermal energy recovery, although these advantages strongly depend on feedstock calorific value and system configuration [31]. Incineration is mainly applicable to relatively dry and combustible organic wastes, especially municipal solid waste with a considerable combustible fraction, refuse-derived fuel, waste plastics, waste rubber, waste textiles, and some hazardous organic residues.

Therefore, incineration is more suitable for wastes with relatively high calorific value, relatively low moisture content, and a strong demand for rapid volume reduction [32]. In contrast, organic wastes with high moisture content, especially untreated food waste, are not suitable for direct incineration because their high water content significantly lowers furnace temperature and increases auxiliary fuel consumption.

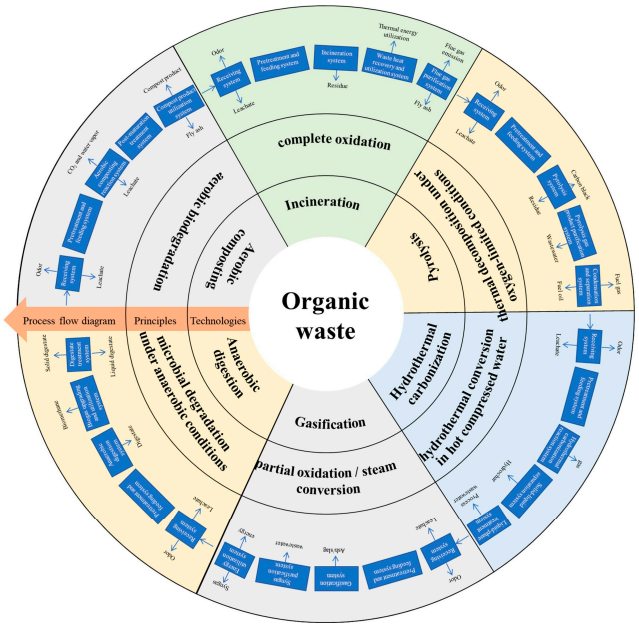


Figure 1. Circular schematic illustration of the major mainstream technologies for organic waste treatment.

The main products generated from incineration include heat, steam, electricity, bottom ash, fly ash, and flue gas. Among these, heat and steam can be used for power generation and district heating, while bottom ash may be further utilized in construction materials after appropriate treatment. By contrast, fly ash usually requires stabilization or secure disposal because it may contain heavy metals, salts, and toxic organic pollutants, and flue gas must undergo strict purification before emission. Enterprises are increasingly focusing on the development and application of carbon reduction technologies aimed at improving energy efficiency, reducing emissions, promoting recycling, and enabling digitalization [33]. Examples include intelligent automatic control systems for incinerators, high-parameter power generation with steam reheating, very low emissions flue gas treatment combining "SNCR + semi-dry acid removal + dry acid removal + activated carbon injection adsorption + baghouse dust collection + wet acid removal + SCR," dry soda-based acid removal with sodium-based fly ash recycling, and co-incineration of multiple types of solid wastes [34–36].

At present, the incineration of organic waste has developed into a diverse process system, encompassing grate furnaces, fluidized beds, and co-processing in cement kilns, with disposal facilities of large, medium, and small scales operating in parallel [37]. This diversity of process configurations improves the adaptability of incineration to different waste compositions and treatment scales, but it also means that technical performance and cost vary significantly across systems. Meanwhile, the practical industrial limitations of incineration do not mainly arise from the combustion reaction itself, but rather from flue gas purification, safe disposal of fly ash, operation and maintenance requirements, and public concern over emission risks [38]. Previous studies have reported that the operating cost of grate furnace incineration is commonly about 16–32 USD/t MSW, while that of fluidized bed incineration is about 10–20 USD/t MSW, indicating that although incineration has a high TRL, its economic and environmental compliance costs are also

relatively high [39]. Taking Nordic waste incineration CHP systems as an example, their high overall energy efficiency depends to a large extent on well-established district heating networks, a condition that is not necessarily available in other regions [29]. Therefore, the high efficiencies reported in experimental or demonstration systems cannot be directly generalized to all industrial scenarios [29].

3.2. Pyrolysis

Pyrolysis is an efficient thermochemical process for converting organic materials into value-added products. Characterized by its high feedstock adaptability, versatile product portfolio, and notable emission reduction and efficiency enhancement, pyrolysis has been widely applied to the treatment of municipal solid waste, crop residues, waste tires, waste plastics, waste paper, and oily sludge. Pyrolysis involves the thermal decomposition of organic materials in the absence of oxygen or under an inert atmosphere, typically within a temperature range of 300–800 °C, enabling the co-production of bio-oil, syngas, and biochar. Among these products, upgraded bio-oil has great potential as a substitute fuel for engines, industrial furnaces, and even aviation applications [40]. The successful implementation of the pyrolysis process depends on multiple parameters, including temperature [41], residence time [42], reaction atmosphere [43], and other operational conditions, all of which collectively determine the yield and selectivity of the desired products.

Moreover, pyrolysis is increasingly employed in the treatment and resource recovery of emerging solid wastes, including spent lithium batteries, waste enameled copper wires, and waste electrical and electronic equipment [44,45]. At present, highly regarded technological equipment in the field includes biomass–ceramic heat carrier rapid pyrolysis systems, skid-mounted batch pyrolysis units for oily sludge, intelligent continuous pyrolysis and carbon black processing systems for end-of-life tires (rubber), atmospheric-pressure pyrolysis technologies for converting waste plastics into fuel oil, key pyrolysis-based recovery technologies and large-scale continuous intelligent equipment for waste enameled copper wires, as well as clean and efficient recycling technologies and equipment for spent lithium-ion batteries [46].

Compared with direct incineration, pyrolysis places greater emphasis on fractionated product recovery and value-added utilization. Therefore, it has attracted widespread attention in the treatment of waste plastics, waste tires, crop residues, the organic fraction of municipal solid waste, and oily sludge [47]. The applicability of pyrolysis is closely related to feedstock properties. In general, this technology is more suitable for organic wastes with relatively low moisture content, high volatile matter content, and favorable calorific value, such as waste plastics, waste tires, waste paper, crop residues, and some oily sludges [48].

In contrast, wastes with high moisture content, high ash content, or large compositional fluctuations are usually less suitable for direct pyrolysis, because pretreatment requires high energy input and may weaken process economics [49]. Pyrolysis products usually include bio-oil, syngas, and biochar, but the product distribution varies substantially among different feedstock systems. For waste plastics, the liquid yield can usually reach 60–80 wt%, and under optimized conditions it may even approach 85 wt%. For waste tires, the typical product distribution is generally 40–60% pyrolysis oil, 10–20% gas, and 20–35% solid char [50,51]. This indicates that pyrolysis has strong resource recovery potential for feedstocks such as waste plastics and waste tires. However, for feedstocks with high moisture content, high ash content, or significant compositional variability, process energy efficiency and economic performance decline markedly. Food waste is a representative example [48]. Although it contains a high proportion of organic matter and thus has certain pyrolysis potential, its high moisture content means that it usually requires dewatering

or drying first, or integration with other processes before entering a pyrolysis system. Therefore, it is more appropriately regarded as a pyrolysable feedstock after pretreatment rather than a preferred feedstock for pyrolysis [52].

The yield and quality of pyrolysis products are jointly influenced by multiple operating parameters, among which temperature, heating rate, solid-phase and gas-phase residence times, reaction atmosphere, feedstock particle size, and catalyst conditions are the most critical [53]. In general, higher temperatures usually favor secondary cracking and increased gas yield, whereas lower temperatures and longer solid-phase residence times are more favorable for increasing char yield. In addition, the reaction atmosphere and residence time can significantly affect secondary reactions of volatiles and the selectivity of target products. Therefore, pyrolysis process design should be optimized according to feedstock composition and target product orientation, rather than being simply generalized to all organic waste systems.

Compared with incineration, pyrolysis products have higher added value. Suitably upgraded pyrolysis oil has potential for industrial thermal applications, boiler combustion, and partial substitution for engine fuels, but its large-scale application is still constrained by the high proportion of oxygenated compounds, limited thermal stability, and high upgrading costs [54]. Therefore, although pyrolysis is close to commercial application in the field of chemical recycling of waste plastics, its industrial maturity for complex mixed organic wastes is still generally lower than that of incineration and anaerobic digestion [55]. Waste tire pyrolysis is a typical example. A high liquid yield does not necessarily mean that the process is fully mature, because sulfur, nitrogen, and polycyclic aromatic hydrocarbons in pyrolysis oil still require further treatment before the oil can meet the requirements for high-quality fuel or chemical utilization [50].

3.3. Hydrothermal Carbonization

Among various thermochemical conversion processes, HTC exhibits distinct advantages in managing solid biomass with high moisture content. The technology is especially applicable to the treatment of wet biomass in which water serves simultaneously as the reaction medium and solvent, for example, industrial sludge with a moisture content above 90% [56]. The process typically operates under autogenous pressure at temperatures ranging from 180 to 250 °C, thereby minimizing the need for energy-intensive pretreatment steps such as drying [56]. The overall reaction pathway involves hydrolysis, dehydration, decarboxylation, and condensation, ultimately converting biomass into a high-carbon-content solid product known as hydrochar. In addition to hydrochar, HTC also generates an aqueous phase rich in dissolved organics and nutrients, together with a minor gaseous fraction mainly composed of CO_2. Previous studies have reported that approximately 60–84% of the initial feedstock carbon can be retained in the hydrochar. In the case of food waste, optimized HTC conditions have been reported to yield hydrochar at 62.05 wt%, with a higher heating value of 21.34 MJ/kg and an energy yield of 81.71% [57].

The hydrochar produced via HTC possesses unique characteristics, including high carbon content, large specific surface area, and abundant oxygen-containing functional groups, which make it suitable for various environmental and energy applications, such as pollutant removal, biofuel production, and soil amendment [58]. The key parameters influencing hydrochar yield and composition include reaction temperature, residence time, and biomass-to-water ratio [59]. Temperature simultaneously governs both the degradation kinetics and the rate of HTC. At lower temperatures, ionic reactions dominate, whereas at higher temperatures, homolytic bond cleavage occurs. With increasing temperature, the yield of solid products decreases while gaseous products increase [60]. However, prolonged residence time does not necessarily enhance the carbon content of hydrochar at a given

temperature, as the optimal duration depends largely on feedstock characteristics and HTC operating conditions. In addition, increasing the initial feedstock concentration improves the absolute conversion rate, enabling the production of hydrochar with the maximum possible yield [61].

However, the industrial feasibility of HTC does not depend only on the efficiency of the main conversion reaction, but also on capital investment for pressurized equipment, slurry handling, solid–liquid separation, and the difficulty of downstream process-water treatment. In sewage sludge treatment, the cost of an integrated HTC + AD configuration was about 94.3 €·t^{-1} sludge, which was higher than that of standalone AD (66.2 €·t^{-1} sludge). This finding indicates that although HTC shows strong process adaptability, it does not always outperform mature biological treatment routes in economic terms [62].

3.4. Gasification

Gasification is a sustainable waste management technology that can significantly reduce greenhouse gas emissions, fossil fuel consumption, and environmental pollution [63].

Under high-temperature conditions, organic waste is converted into syngas, a mixture rich in H_2, CO, CH_4, and CO_2, through partial oxidation in the presence of gasifying agents such as air, oxygen, or steam. This syngas can be utilized for various purposes, including the production of high-value fuels or electricity generation [64,65]. Gasification is mainly applicable to feedstocks that are relatively dry and rich in carbon, such as biomass, refuse-derived fuel, municipal solid waste with a considerable combustible fraction, and selected industrial organic residues. In addition to syngas, the process may also generate char, ash or slag, and tar-containing byproducts, which require appropriate downstream management depending on reactor type and operating conditions. Cleaned syngas can be used for heat and power generation, hydrogen production, or downstream fuel and chemical synthesis. Biomass or waste gasification typically shows an energy efficiency in the range of about 40–70%, while representative cold gas efficiency values are often reported around 63–66%. In addition, an approximate hydrogen yield of about 100 kg H_2 per tonne of dry biomass has been reported for gasification-based hydrogen production, and some engineering studies have also reported carbon conversion efficiencies of about 80–85%. These performance indicators suggest that gasification is particularly advantageous for feedstocks that are relatively dry, rich in carbon, and compositionally stable [66–68].

The composition and quality of syngas are strongly influenced by gasification temperature, with higher temperatures generally improving gas quality [69]. Studies by Lin et al. and Marculescu et al. indicated that 700–900 °C is the optimal temperature range for the gasification of MSW [70,71]. Most researchers suggest that 900 °C yields the best performance, although the optimal temperature may vary depending on the gasifier type. For instance, Singh et al. found that when using a downdraft gasifier to process food waste, the maximum hydrogen yield was achieved at 800 °C [72].

Gasification efficiency also improves with increased residence time, up to a certain threshold beyond which it stabilizes [73–75]. The optimal residence time varies across gasifier types [76]. Khonde et al. reported that in a fixed bed gasifier, a residence time of 48 s maximized hydrogen-rich syngas production and promoted efficient tar cracking. In bubbling fluidized-bed gasifiers, residence times of 40–60 s were found to be ideal for achieving effective mixing between gas and solid phases, thereby enhancing reaction rates. Conversely, Chutichai et al. observed that circulating fluidized-bed gasifiers generally exhibit shorter residence times [77].

In addition to temperature and residence time, the type and dosage of catalysts greatly influence gasification efficiency and syngas quality, as each catalyst possesses unique advantages and limitations [78,79]. For example, nickel-based catalysts are highly

effective in tar decomposition and hydrogen yield enhancement; despite their high cost, they are durable and perform well at high temperatures. Calcium-based catalysts, on the other hand, are particularly suitable for sulfur capture and for mitigating the release of corrosive compounds during gasification. However, they can react with ash components such as silica (SiO_2) and alumina (Al_2O_3) to form low-melting-point eutectic mixtures, potentially leading to slagging and fouling issues. After decades of development, pyrolysis–gasification technology and its associated equipment have become relatively mature [80]. The main types of large-scale gasifiers currently in use include updraft and downdraft fixed-bed gasifiers [81], fluidized-bed gasifiers [82], entrained-flow gasifiers, turbulent-bed gasification–incineration systems, and vertical rotary pyrolysis–gasification furnaces [80].

However, under real industrial conditions, the limitations of gasification are usually more complex than those suggested by laboratory studies. These limitations include the high demand for feedstock drying, the difficulty of tar control, the risks of slagging and fouling, the high cost of gas cleaning, and the strong dependence of continuous operation on feedstock uniformity [83–85]. In the case of biomass gasification for hydrogen production, the representative value of about 100 kg H_2 per tonne of dry biomass is generally obtained under optimized feedstock and process conditions, whereas this level is often difficult to maintain stably when treating organic wastes with high ash, high chlorine, or high moisture contents. Therefore, although gasification has clear advantages in energy recovery and syngas production, its industrial performance still depends strongly on feedstock quality, pretreatment requirements, reactor configuration, and downstream gas cleaning strategy [83].

3.5. Anaerobic Digestion

AD is a biological decomposition process in which hydrolytic bacteria, acetogenic bacteria, and methanogenic archaea work synergistically to convert organic matter into CH_4 and CO_2 [86]. Producing biogas from easily degradable organic wastes, such as kitchen waste and livestock manure, is one of the most common methods of biomass energy recovery [87,88]. AD is particularly suitable for feedstocks with high moisture content and high biodegradability, including food waste, kitchen waste, livestock manure, sewage sludge, and other wet organic residues. The main products generated by AD include biogas and digestate. Biogas, mainly composed of CH_4 and CO_2, can be used for heat and power generation or upgraded to biomethane, whereas the digestate can be further utilized as an organic fertilizer or soil amendment after appropriate treatment and stabilization [89]. Reviews of food-waste digestion have reported methane yields commonly in the range of 282–311 L CH_4/kg VS under typical conditions, whereas higher values can be achieved in intensified or two-phase systems. In representative enhanced systems, methane yields as high as 640.31 L CH_4/kg VS have been reported, together with volatile solids removal efficiencies of up to about 85% and methane contents of about 75% in the biogas. These results indicate that AD has clear advantages for treating feedstocks with high moisture content and high biodegradability [90].

The AD process depends on various operational parameters, including temperature and pH, as well as substrate characteristics such as the carbon-to-nitrogen (C/N) ratio, volatile fatty acid concentration, and organic loading rate. Proper process control is essential to ensure the viability and activity of the involved microbial communities. Temperature is a critical factor in AD, as it not only determines the thermodynamic equilibrium of biochemical reactions but also affects enzyme functionality. In general, increasing the temperature enhances digestion efficiency. The pH level serves as an indicator of system stability, and each microbial group has its own optimal pH range. The suitable pH range for hydrolytic bacteria is 5.2–6.3, while acetogenic bacteria and methanogens thrive in the range

of 6.6–8.0, with most methanogens performing best between 6.5 and 7.2 [91]. Maintaining a neutral pH environment is thus crucial for sustaining a robust methanogenic population. Additionally, a balanced C/N ratio is required to maintain a stable environment and proper nutrient balance for microbial growth, ensuring a stable AD process [92].

In recent years, AD technology has made significant progress, including efficient pretreatment technologies, near-simultaneous co-digestion of multiple substrates, single-phase and two-phase anaerobic digestion, and mesophilic to ultra-high temperature and high-solids or dry digestion systems. The range of reactor configurations now extends from traditional continuous stirred-tank reactors used for wet digestion to next-generation multistage and simulated dry fermentation systems, which are currently under active research and pilot-scale demonstration [93]. However, the industrial limitations of AD are mainly associated with long-term process stability and digestate management. For feedstocks such as food waste, acidification, foaming, ammonia inhibition, long-chain fatty acid inhibition, impurity removal, and the downstream utilization or treatment of digestate are often the key factors determining process economics and engineering reliability. Therefore, although AD is one of the most mature treatment routes for wet biodegradable wastes, its practical performance still depends strongly on substrate characteristics, process control, and downstream residue management [94].

3.6. Aerobic Composting

Composting is an established biological stabilization route for biodegradable organic wastes, through which organic matter can be converted into relatively stable fertilizer-like products under controlled aerobic conditions [95]. The composted products can serve as soil conditioners or nutrient sources for crops [96]. During the composting of organic waste, several factors, including the nutrient composition and physicochemical properties of the raw materials, temperature, carbon-to-nitrogen (C/N) ratio, pH, aeration rate, and moisture content, significantly influence both the process dynamics and the quality of the final product [97,98]. Some studies have suggested that adjusting operational parameters alone is less effective than the application of additives in improving compost quality [99]. Physical, chemical, and biological additives can enhance humification during the composting process [100,101].

For instance, the use of metal-based additives in composting has recently become a research hotspot. MnO_2 acts as a catalyst precursor for humic substance polymerization [102], while $FeSO_4$ promotes humification during cattle manure composting [103]. Nano zero-valent iron (nZVI) can enhance microbial migration and enrich functional microbial communities in compost, thereby improving system stability and redox efficiency [104]. Al_2O_3, when used as a reusable filler in sludge composting, effectively stabilizes Cd and reduces its mobility [105]. These results indicate that additive-assisted composting can improve nutrient retention, humification, and heavy metal stabilization, rather than merely accelerating organic matter degradation.

Recent studies have also provided evidence that process optimization can simultaneously improve compost quality and reduce environmental emissions. For example, a condensation reflux composting system reduced NH_3 emissions by 59.3% and increased the total nitrogen content of the final compost product by 19.4%, indicating that improved reactor design can enhance nitrogen retention while mitigating gaseous losses [106]. In addition, the addition of mature compost markedly accelerated compost maturity: the germination index (GI) of the treated compost reached 96.36% on day 12, whereas the control only reached 75.08% on day 33, indicating that maturity was achieved 22 days earlier. The final GI of the treated group further increased to 119.37%, which was substantially higher

than that of the control group (81.29%), confirming that this strategy can both shorten composting time and improve final compost quality [107].

In addition to additive optimization, research and application in the field of aerobic composting are increasingly focused on process optimization, technological innovation, and reactor design, showing a trend toward diversification, high efficiency, and intelligent control [108]. Widely adopted advanced technologies and systems include multi-stage microbial inoculation and directional humification, hyperthermophilic composting, intelligent membrane-covered composting, multi-chamber mechanically enhanced rapid composting, integrated intelligent aerobic fermentation systems, and multi-layer static aerobic fermentation [109]. These methods enhance composting performance by strengthening microbial activity, introducing innovative process designs, and employing intelligent monitoring and control systems. Collectively, they support both centralized and decentralized treatment modes, enabling composting systems to adapt to diverse regional environments and operational scales [110]. However, composting performance still depends strongly on feedstock composition, aeration control, moisture management, and additive strategy, and poorly controlled systems may still suffer from odor emissions, nitrogen loss, greenhouse gas release, and inconsistent product quality [111]. Therefore, aerobic composting is best understood as a mature and versatile stabilization technology whose effectiveness depends on process control and product-quality management rather than on simple waste piling alone [112].

Overall, there is no absolute superiority or inferiority among conventional organic waste treatment technologies. Incineration and gasification are more suitable for relatively dry feedstocks with higher calorific values or for systems targeting energy or syngas recovery. Pyrolysis is more suitable for wastes with low moisture content, high carbon content, and high volatile matter, but it places higher demands on product upgrading and continuous operation. HTC shows clear advantages for wastes with high moisture content, whereas its scale-up bottlenecks mainly lie in high-pressure systems and liquid-phase management. AD is the most mature technology for treating wet and readily biodegradable feedstocks, but its practical feasibility is determined by long-term operational stability and digestate management. Aerobic composting has advantages in stabilization and nutrient recovery, but environmental emissions and limited product marketability constrain its degree of value-added utilization.

Table 1. Overview of Mainstream Technologies for Organic Waste Treatment.

Mainstream Technologies	Process Overview	Suitable Feedstocks	Primary Products	Main Strengths	Drawbacks	Technology Readiness Level	Efficiency Characteristics	Scalability	Ref.
Incineration	Solid wastes are subjected to complete oxidation at elevated temperatures in the presence of excess oxygen.	Municipal solid waste and hazardous wastes;	Heat energy, flue gas, bottom ash, and fly ash.	Rapid heat release, high energy recovery potential, and strong adaptability to diverse waste compositions.	High operational costs, with potential formation of dioxins (PCDD/Fs), nitrogen oxides (NOx), and acidic gases.	High	The volume-reduction effect is significant, but energy-utilization efficiency is not always ideal.	High. It is most suitable for large-scale continuous operation.	[113,114]
Pyrolysis	The thermal decomposition of organic wastes at medium to high temperatures (300–800 °C) in the absence of oxygen or under an inert atmosphere.	Biomass, plastics, rubber, and other organic solid wastes;	Bio-oil, syngas, and biochar.	Enables the simultaneous recovery of energy and materials	Relatively high energy consumption, with product physicochemical properties sensitive to process conditions	Relatively high	Product regulation is relatively strong, but the efficiency depends heavily on temperature, residence time, and reactor design.	Relatively high. It has scale-up potential, but product stability and downstream utilization are still affected by operating conditions	[115–117]
HTC	Treatment of organic wastes with high moisture content in an aqueous medium at elevated temperatures (180–250 °C) and high pressures, typically under autogenous conditions.	Kitchen waste, sewage sludge, and agricultural residues;	Hydrochar and aqueous-phase organics.	Low energy consumption during the process, particularly suitable for treating organic wastes with high moisture content.	Long reaction cycles, high operation and maintenance costs, and potential pollution from the liquid phase.	Moderate to high	It has clear advantages for feedstocks with high moisture content, with relatively high conversion efficiency, and is suitable for wet waste treatment.	Moderate. There are still barriers in continuous operation and system integration between laboratory and industrial scales.	[118–120]

Table 1. *Cont.*

Mainstream Technologies	Process Overview	Suitable Feedstocks	Primary Products	Main Strengths	Drawbacks	Technology Readiness Level	Efficiency Characteristics	Scalability	Ref.
Gasification	The partial oxidation or reforming of solid wastes at elevated temperatures (800–1200 °C) in the presence of gasifying agents such as air, oxygen, or steam, resulting in the generation of a combustible syngas primarily composed of H_2, CO, CH_4, and CO_2.	Biomass, municipal solid waste, and other organic solid wastes;	Syngas (CO + H_2) and slag.	Converts solid wastes into syngas, with the resulting ash and slag potentially utilized in construction materials or as road fill.	High cost, with the potential formation of toxic compounds	High. Biomass gasification has generally reached TRL 8–9, although maturity still depends on gasifier type and feedstock quality.	Gasification can achieve relatively high carbon conversion and favorable energy-utilization efficiency, but performance is strongly influenced by reactor type, gasifying agent, feed particle size, and moisture content.	Relatively high. Conventional gasification has been demonstrated from pilot to commercial scale, but feedstock heterogeneity, tar removal, and long-term continuous operation remain key barriers to further scale-up.	[121,122]
AD	The stepwise microbial decomposition of organic wastes in the absence of oxygen, leading to the production of biogas (primarily CH_4 and CO_2) and stabilized digestate.	Food waste, livestock manure, agricultural residues, and sewage sludge.	Biogas (CH_4 + CO_2), digestate liquid, and digestate	Converts organic wastes into biogas, with the fermentation residues usable as organic fertilizers or soil amendments	Feedstock limitations and poor operational stability	High	The technology is stable, but the reaction rate is relatively slow and sensitive to operating conditions.	Relatively high. It has already been widely applied in engineering practice, but large-scale and efficient operation is still constrained by process control.	[123–125]

Table 1. *Cont.*

Mainstream Technologies	Process Overview	Suitable Feedstocks	Primary Products	Main Strengths	Drawbacks	Technology Readiness Level	Efficiency Characteristics	Scalability	Ref.
Aerobic composting	The microbial degradation of organic wastes under oxygen-rich conditions, during which biodegradable matter undergoes thermophilic aerobic phases and is progressively stabilized into mature humus-like substances.	Agricultural residues, garden waste, and food waste.	Matured compost (organic fertilizer).	Environmentally friendly, technically simple, and broadly applicable	Generation of odorous gases and inconsistent product quality	High	It is mainly oriented toward nutrient recovery, while its energy-recovery capacity is limited.	Relatively high. It is flexible in scale and can be applied in both decentralized and centralized systems.	[126–128]

4. Advanced and Intensified Technologies for Organic Waste Valorization

Conventional organic waste treatment technologies, such as incineration, pyrolysis, gasification, AD, and aerobic composting, have achieved significant progress in waste volume reduction, energy recovery, and resource utilization. However, these methods still face limitations when treating high-moisture-content, hazardous, or compositionally complex wastes. For instance, incineration can generate harmful by-products such as dioxins, gasification and pyrolysis may produce tar, and AD and composting are constrained by long reaction times and relatively low energy recovery efficiency [129]. To address these limitations, advanced or intensified technologies such as MAP, plasma gasification, SCWG technology and FJH technology have shown unique advantages. Various advanced and intensified methods for treating organic waste are shown in Table 2 and discussed in detail below:

Table 2. Advanced and intensified technologies for solid waste treatment.

Advanced or Intensified Technologies	Process Overview	Advantages	Application Scenarios	Research Progress	Maturity	Scalability	Ref.
MAP	MAP achieves uniform heating of waste materials through microwave irradiation, resulting in the thermal decomposition into bio-oil, syngas, and biochar.	Rapid and uniform heating with high reaction efficiency; low tar formation; enhanced selectivity toward gaseous or liquid products.	High-calorific-value wastes suitable for further upgrading and valorization.	Currently at laboratory and pilot-scale stages	Advanced and intensified technologies	Moderate to relatively low. Scale-up, heating uniformity, and continuous operation are the main challenges.	[130,131]
Plasma Gasification	Plasma gasification employs the ultra-high temperature (>3000 °C) generated by plasma torches to decompose solid waste, yielding high-purity syngas and inert vitrified slag	Complete decomposition of organic matter at ultra-high temperatures, with near-total elimination of pollutants such as dioxins; production of clean syngas with minimal tar formation.	Hazardous waste and medical waste.	Pilot-scale demonstrations have been conducted, with partial commercialization achieved	Moderate to high. The technology has established a certain level of maturity, but overall it remains an emerging waste-to-energy pathway with limited commercialization.	Moderate to relatively low. Scale-up, continuous operation, and system lifetime remain key challenges.	[132,133]
SCWG	SCWG decomposes organic matter under supercritical water conditions (T > 374 °C, P > 22 MPa), producing high-calorific-value syngas.	Efficient treatment of wastes with high moisture content without the need for drying; high hydrogen yield; near-complete conversion of feedstock.	With high moisture content, difficult-to-dry organic wastes.	Currently at the pilot-scale stage, with experimental applications on sewage sludge and food waste	Moderate/emerging. It has broad application prospects, but commercialization is still constrained by engineering challenges.	Moderate to relatively low. High pressure, corrosion, salt precipitation, and clogging limit scale-up.	[134,135]

Table 2. *Cont.*

Advanced or Intensified Technologies	Process Overview	Advantages	Application Scenarios	Research Progress	Maturity	Scalability	Ref.
FJH	FJH enables ultrafast electrothermal conversion	Extremely short processing time (millisecond scale), high energy efficiency, and enables recovery of carbon nanomaterials and gaseous products.	High-value resource recovery/carbon material upgrading	At the laboratory research stage.	Moderate/emerging. It is currently mainly at the bench scale and in the exploratory stage of novel scale-up.	Low to moderate. Continuous operation and large-scale stable production remain the main bottlenecks.	[136,137]

4.1. MAP Technology

Conventional pyrolysis typically requires high temperatures of 300–700 °C and prolonged reaction times ranging from several hours to over ten hours. This heating approach not only limits reaction efficiency but also affects product quality, presenting certain limitations in practical applications [138].

MAP combines microwave irradiation with conventional pyrolysis, enabling internal heating of the feedstock. This approach reduces energy loss associated with heat transfer from external sources [139]. The MAP process is illustrated in Figure 2. Unlike conventional pyrolysis, where heat is transferred from the exterior to the interior through a thermal gradient, microwave energy penetrates the material and is converted into heat within the core. This internal heating is mainly associated with dipole rotation and ionic conduction, through which electromagnetic energy is transformed into thermal energy inside the material, thereby reducing thermal inertia and, under suitable conditions, improving heating uniformity and shortening the time required to reach the target pyrolysis temperature [140]. Polar molecules (e.g., water, hydrocarbons) or conductive components (e.g., carbon black, residual oils) undergo dipole polarization and dielectric loss in the electromagnetic field, thereby converting electromagnetic energy into thermal energy [141]. However, many biomass and plastic feedstocks do not absorb microwaves efficiently because of their relatively low dielectric properties, and therefore microwave absorbers such as activated carbon, graphite, silicon carbide, or metal oxides are often required to achieve stable heating and effective pyrolysis performance [142,143]. Compared with conventional pyrolysis, MAP is generally characterized by volumetric and selective heating, faster thermal response, and in many cases higher gas yields, lower tar formation, or improved product quality; nevertheless, these advantages are strongly dependent on feedstock type, microwave power, absorber/catalyst selection, and reactor design [144,145]. Rapid pyrolysis of organic waste into gaseous, liquid, and solid products under oxygen-limited or anaerobic conditions [146,147]. MAP has been successfully applied to the treatment and resource recovery of various organic wastes, including agricultural residues, food waste, plastics, and sewage sludge, and has become one of the important research directions for the valorization of organic waste in recent years.

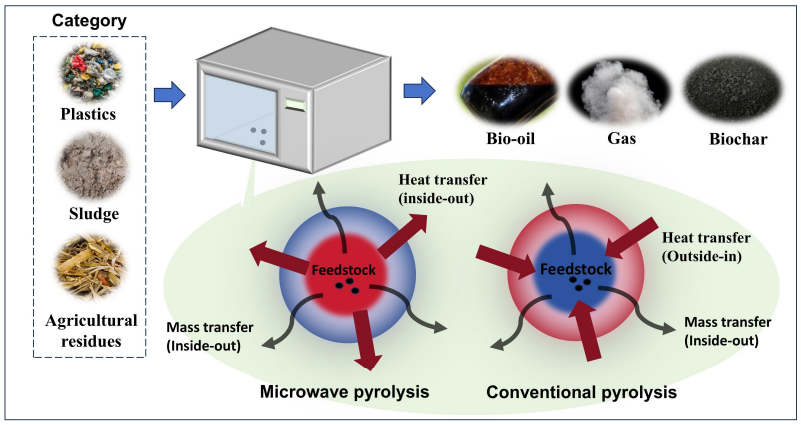


Figure 2. MAP process for organic waste.

4.1.1. Treatment of Biomass Waste via MAP

Biomass waste is an abundant renewable resource that can be converted into syngas, bio-oil, and solids with high carbon content for use as fuels, chemical feedstocks, and carbon precursors [148]. Due to its wide availability and conversion potential, biomass has attracted significant attention, and MAP has been regarded as an intensified pyrolysis route with comparative advantages over conventional pyrolysis in selected aspects of biomass processing [149].

Biomass wastes, such as macroalgae, microalgae, agricultural residues, and forestry residues, typically contain large amounts of cellulose, hemicellulose, and lignin, which often lead to relatively low heating efficiency and prolonged reaction times under conventional thermal pyrolysis conditions [150–154]. According to Abdelsayed et al., MAP produced higher gas yield, lower tar yield, and comparable carbonization yield [155]. Dong and Xiong reported that, at comparable heating rates, the Ea for MAP was 24.5 kJ/mol, significantly (50.6%) lower than the 49.6 kJ/mol observed for the conventional method [156]. From the perspective of bioenergy production, syngas and bio-oil are the most important end products. The gaseous products generated from different biomass feedstocks through MAP generally contain H_2, CO, CH_4, CO_2, and light hydrocarbons, though the yield and composition vary among biomass types. Studies have reported that rice straw primarily produces CO_2 and H_2, whereas bagasse and corn straw mainly yield CH_4 and CO as major gaseous components [157]. MAP is particularly advantageous when biological matter is converted into gaseous products, with gas production rates 1.1–4.2 times higher than conventional pyrolysis, and under certain conditions, it produces higher levels of H_2, CO, and CH_4 components and lower levels of CO_2 components [145,158].

The net yield and physicochemical properties of bio-oil depend largely on the intrinsic structural and biochemical composition of the biomass. The pyrolysis of cellulose and hemicellulose generates a higher oil yield compared with lignin, whose high structural stability leads to a more complex decomposition process, eventually forming stable char [159]. Therefore, the comparative performance of MAP is not universal across all biomass types, because product distribution still depends strongly on the relative proportions of cellulose, hemicellulose, and lignin as well as on the dielectric response of the feedstock [157,160]. Interestingly, the MAP of different lignocellulosic biomass types, such as rice husk, rice straw, corn stalk, spent coffee grounds, bamboo leaves, bagasse and sugarcane peel, produces nearly the same amount of solid char. Factors such as temperature [161], heating rate [162], residence time, particle size [163], and the type of microwave absorber significantly influence the yield and composition of gas, oil, and char products [163].

Furthermore, the application of catalysts can enhance MAP efficiency by promoting chemical reactions involved in the pyrolysis mechanism. Currently, the most widely

studied catalyst categories in MAP include zeolite-based, metal/metal oxide-based, and carbon-based catalysts. Research has shown that zeolite catalysts enhance the production of fuel-range hydrocarbons by increasing the content of aromatic and isomerized aliphatic hydrocarbons, whereas carbon-based catalysts, due to their porous structure and surface functional groups, effectively absorb microwaves and enhance catalytic activity [164,165].

Carbon-based additives are particularly important in biomass MAP because they can act not only as catalysts or catalyst supports, but also as microwave absorbers that improve energy coupling, promote local hot spots, and lower the apparent temperature required for pyrolysis reactions [166]. Despite these advantages, the practical application of biomass MAP is still limited by feedstock-dependent dielectric properties, hot spot formation, uneven electromagnetic field distribution in large reactors, and the need for suitable microwave absorbers or catalysts, meaning that its advantages are highly condition-dependent [148].

4.1.2. Application of MAP in Sewage Sludge Conversion

Sewage sludge is a heterogeneous organic waste with relatively high energy potential [167]. It is a waste with high moisture content and high organic load generated from wastewater treatment systems, and its treatment and resource utilization have long been a major technical challenge in solid waste management [168]. A representative study reported that aerobically digested sewage sludge contained about 71% moisture, 31.2% ash, 62.3% volatiles, and a dry heating value of 16.68 MJ/kg, indicating that sludge is simultaneously a wet feedstock and a potentially recoverable energy carrier [169]. MAP can effectively remove moisture from sludge within a short period, thereby improving the yield of pyrolytic products and enhancing energy conversion efficiency [170]. After wet sludge was exposed to 1000 W microwave irradiation for 6 min, the average heating rate reached approximately 200 °C/min, and the maximum temperature reached 1000–1040 °C, indicating the strong heating-enhancement potential of MAP for wet sludge [171]. Moreover, because water molecules and other polar or conductive components in sludge can couple effectively with the microwave field, MAP can accelerate internal heating and improve pyrolytic reaction efficiency relative to conventional externally heated systems [172]. This advantage is particularly relevant for sewage sludge because conventional heating must first overcome the large thermal burden associated with water evaporation, whereas microwave heating can deposit energy directly into microwave-responsive phases within the sludge matrix [173]. Moreover, due to the polarization effects of water molecules under microwave heating, MAP reduces the sintering of organic components in sludge, increases the efficiency of pyrolytic reactions, and significantly decreases the formation of tar and other harmful by-products [174]. MAP has also been reported to reduce tar formation and improve gas-phase conversion, which is favorable for the recovery of cleaner gaseous products from sewage sludge [175]. In addition, sludge composition strongly affects MAP performance: Biochar yield can be negatively correlated with organic content and positively correlated with ash content in different sewage sludge feedstocks, indicating that product distribution is highly dependent on sludge characteristics [176]. Without a suitable microwave absorber, sludge may not be effectively heated under microwave irradiation; Domínguez's research clearly indicates that sludge without an absorber cannot be heated above 200 °C, while graphite or sludge-derived carbonized materials achieve highly efficient heating and pyrolysis [169]. This means that sewage sludge MAP still faces practical constraints related to absorber selection, feedstock variability, and reactor-scale heating uniformity, and these issues must be addressed before it can be regarded as a robust large-scale sludge-to-fuel technology [177].

4.1.3. Conversion of Plastic Waste Through MAP

MAP of plastic waste has become one of the current research hotspots. Common plastics such as polyethylene and polypropylene can be effectively converted into high-value syngas under microwave heating [178–180]. Similarly, Ding et al. demonstrated that plastic waste can be converted into efficient syngas (CO and H_2) and biochar. Compared with conventional pyrolysis, MAP can increase hydrogen yield and reduce tar formation [181]. MAP of plastic waste has become one of the major research hotspots in thermochemical waste valorization. In contrast to biomass-oriented MAP, the main attraction of plastic MAP lies in the high carbon and hydrogen content of plastics, which makes them suitable for the production of liquid hydrocarbons, hydrogen-rich gases, and carbonaceous products [182]. Common plastics such as polyethylene, polypropylene, and polystyrene can be converted into liquid oils, gaseous products, and char under microwave heating, although the dominant target product differs markedly among polymer types and operating conditions [183]. Compared with conventional pyrolysis, MAP can in many cases accelerate plastic cracking, shorten startup time, improve heating efficiency, and promote the formation of hydrogen-rich gases while suppressing tar formation [184]. A representative study on polypropylene reported a hydrogen volume fraction of 68.2 vol%, a hydrogen yield of 28.8 mmol/g PP, and a hydrogen efficiency of 38.4% under microwave-assisted catalytic pyrolysis, demonstrating that MAP can indeed outperform conventional plastic pyrolysis when hydrogen-oriented conversion is the target [185].

The degree of heating depends on the dielectric strength of the material [109]. Due to this property, microwave heating shortens reaction time in pyrolysis, thereby improving process efficiency. However, this advantage is strongly material-dependent, because many common plastics, especially nonpolar polymers such as polyethylene and polypropylene, have very low dielectric loss and are nearly transparent to microwaves [186].Since plastics typically exhibit low dielectric strength, their microwave pyrolysis usually involves combining them with highly microwave-absorbing dielectric materials, such as silicon carbide, activated carbon, or iron oxide as microwave absorbers [187]. Pure plastic raw materials can reach temperatures of up to approximately 200 °C under microwave irradiation unless a suitable absorber is present [188]. This explains why carbon materials, silicon carbide, magnetite, iron powder, and other microwave sensors are often added to practical MAP systems. Because the composition of plastic waste varies greatly, the heating efficiency differs among materials when mixed with these absorbers [189]. The role of absorbers is not limited to initiating heating; they also influence reaction rate and product distribution. For example, carbon absorbers have been reported to generate faster heating and shorter residence times than some alternative absorbers, while different absorber types can shift the balance between oil, gas, and char formation [184].

Reaction temperature is the most critical parameter in the pyrolysis of various plastics, as it significantly affects both the quality and quantity of the products [190–192]. Optimizing temperature conditions is essential depending on the desired target products. For instance, Ding et al. conducted catalytic MAP of low-density polyethylene waste and observed that the maximum oil yield occurred at 500 °C [193]. Fan et al. studied MAP of PS plastics and found that oil yield increased with temperature, reaching about 99% at 460 °C [194]. This result is consistent with broader review data indicating that PS is one of the most microwave-responsive plastics and can achieve oil yields as high as 98.78 wt%, with the oil dominated by C8–C16 compounds and a large proportion of styrene-derived aromatics [195]. More generally, plastic MAP can produce liquid oil yields up to 95 wt%, and in some cases the liquid products exhibit a high heating value of 41.58 MJ/kg, with physicochemical properties comparable to diesel-like fuels [188]. In addition to temperature, factors such as microwave power [196,197], reaction time, catalyst type [198], particle size [199], and reactor

configuration are major parameters influencing the production of liquid oil and gaseous products from MAP. Proper control of these parameters is necessary to achieve the desired product distribution [183]. Despite these advantages, the practical deployment of plastic MAP is still limited by the weak intrinsic microwave absorbance of many polymers, the need for suitable absorbers or catalyst–absorber systems, composition-dependent heating behavior in mixed plastic streams, hotspot formation, and the difficulty of scaling laboratory reactors to larger continuous systems [200].

Compared with conventional pyrolysis, MAP is mainly distinguished by its volumetric heating mode, which can reduce thermal gradients and accelerate reaction rates. Under suitable conditions, MAP may provide faster heating, lower apparent activation energy, improved product selectivity, and reduced tar formation. However, its performance is highly dependent on feedstock characteristics and operating parameters, and its scale-up is still limited by microwave penetration depth, field non-uniformity, hotspot formation, and reactor cost. A comparison between conventional pyrolysis and MAP is provided in Table 3. In addition to feedstock-specific performance, the practical viability of MAP should also be evaluated from technoeconomic and life-cycle perspectives.

Table 3. Comparison between conventional pyrolysis and MAP.

Aspect	Conventional Pyrolysis	Microwave Pyrolysis	Ref.
Heating mechanism	Heat is supplied externally and transferred inward mainly through conduction and convection, producing an outside-to-inside temperature gradient.	Microwave energy is converted directly into heat within microwave-responsive phases of the material through dielectric heating, dipole rotation, and ionic conduction, leading to volumetric heating.	[140]
Heating rate	Typically slower; representative reviews report about 5–20 °C/min for conventional thermal pyrolysis in comparative summaries, while slow pyrolysis may be below 1–2 °C/s.	About 60–80 °C/min in practical MAP systems, and up to 330 °C/s in specific carbon material studies.	[148]
Temperature control	Surface temperature is often higher than the core, which may cause non-uniform heating and larger thermal gradients.	The core may become hotter than the surface, which can improve internal heating efficiency; however, field non-uniformity may still create hotspots in larger systems.	[7]
Operating temperature	Usually requires sustained external heating, often in the range of 300–800 °C, depending on slow/fast pyrolysis modes.	It can operate at relatively low temperatures (200–800 °C).	[7]
Energy efficiency	Higher external heat demand, with representative pilot scale values of ~1.3–3.0 MJ kg^{-1} feed depending on heat recovery strategy.	Often lower energy consumption than conventional heating, with up to 2.5-fold lower energy consumption reported in LCA based comparisons; however, direct biomass MAP may still exhibit low overall microwave heating efficiency (<40%) when microwave absorption is poor.	[140,143,201,202]
Bio-oil quality	Bio-oil often contains higher moisture, oxygen, acidity, and broader degradation products due to uneven heating and prolonged secondary reactions.	MAP can yield cleaner bio-oil with more favorable composition and, in some reports, higher aromatic/phenolic selectivity and fewer PAHs.	[203]
Syngas composition	Typically contains CO_2, CO, H_2, and light hydrocarbons	Often shows higher fractions of H_2, CO, and CH_4, with reduced CO_2 under suitable conditions	[203]

Table 3. *Cont.*

Aspect	Conventional Pyrolysis	Microwave Pyrolysis	Ref.
Biochar properties	Higher I_D/I_G (0.85–0.89) and lower BET surface area (~288.6 m^2 g^{-1})	Lower I_D/I_G (0.78–0.84) and higher BET surface area (~455.9 m^2 g^{-1})	[140,204]
Environmental impact	Often associated with higher energy demand and greater CO_2 emissions from prolonged external heating	May reduce energy demand and life-cycle CO_2 emissions in selected pathways, depending on electricity source and reactor configuration	[171,205]
Process scalability	Well established for large-scale operation, although often energy intensive	Scale-up remains challenging because of microwave penetration limits (1–2 cm), field non-uniformity, hotspot formation, and high reactor/material costs	[148]

Recent techno-economic assessment (TEA) and life-cycle assessment (LCA) studies suggest that the economic and environmental performance of MAP systems are highly pathway-dependent rather than universally favorable. In carbon-removal-oriented applications, such as industrial biochar production from olive pruning, attributional LCA showed that up to 2.68 t CO_2e could be permanently removed per ton of biochar on a dry basis under a cradle-to-grave boundary, indicating strong climate mitigation potential when stable carbon sequestration is the main objective [206]. In contrast, for commercial co-pyrolysis of food waste and LDPE, the total energy use was reported as 0.54 kWh per kg of feedstock, with drying and pyrolysis contributing 91% of the overall energy demand, suggesting that pretreatment and thermal conversion remain the dominant sources of environ-mental and economic burden in practical MAP systems [207]. For liquid-fuel-oriented routes, MAP of pine sawdust followed by upgrading to biodiesel showed a cradle-to-gate global warming potential of 1.18 kg CO_2-eq per kg biofuel, confirming that electricity input and upgrading steps strongly influence the final environmental profile [208].

TEA results also show that energy supply configuration can substantially affect profitability: in a solar-powered microwave pyrolysis case using corn stover, the payback period was estimated at 0.5 years under grid-connected operation but increased to 1.6 years under solar-powered conditions, although the latter provided greater CO_2 mitigation benefits [209]. More broadly, comparison with slow pyrolysis biochar systems in Great Britain further indicates that economic viability is highly sensitive to system boundaries and carbon-credit assumptions, with marginal carbon sequestration costs below £75 per tCO_2e and a potential contribution of 0.6–1.9% of the UK 2050 carbon removal target [209]. Overall, existing TEA and LCA evidence indicate that the comparative advantage of MAP depends strongly on product orientation, electricity source, process energy demand, coproduct handling, and accounting boundary, rather than on the microwave process alone.

4.2. Plasma Technology

Plasma is generally regarded as the fourth state of matter, distinct from solids, liquids, and gases. It is an energized ionized gas, formed by applying sufficient energy, typically via gas discharge, to ionize the gas, thereby separating electrons from neutral gas molecules and atoms [210]. Plasma contains charged particles, including free electrons and positive and negative ions, which respond to applied electric and magnetic fields. These particles can efficiently decompose organic matter in a very short time, converting it into products such as syngas, liquid fuels, and biochar [149]. Because of its high temperature, high energy density, and abundance of reactive species, plasma gasification can promote the conversion of tar, char, and refractory organics more effectively than conventional gasification, especially at relatively low oxygen concentrations [211]. Studies by Mallick and Chu et al. have reported tar-free syngas with H_2 and CO contents of 42.6 vol% and 44.06 vol%, respectively,

in CO_2 thermal plasma gasification, while steam plasma co-gasification increased the H_2 proportion by 4.96–16.95% and reduced chlorine release by 1.84–41.41% relative to the weighted sum of mono-gasification [212,213].

Compared with conventional pyrolysis and gasification technologies, plasma systems generally show lower tar formation and stronger pollutant destruction capability, which makes them particularly relevant for difficult-to-treat wastes such as biomass residues, rubber waste, plastics, and hazardous organic wastes [214]. Recent studies have reported that plasma gasification can substantially improve conversion performance under optimized conditions. For example, steam plasma entrained-flow gasification increased carbon conversion efficiency from 82% to 95%, raised the H_2/CO ratio to 1.03, and achieved a cold gas efficiency of about 80% under fully steam-plasma conditions [215].

These results indicate the technical potential of plasma gasification. For these reasons, plasma treatment has become an important research direction for difficult-to-treat organic solid wastes and is increasingly considered a promising intensified route for syngas-oriented waste valorization [216,217]. However, its practical deployment remains limited by high electricity demand, plasma torch and electrode erosion, refractory wear, reactor cooling requirements, challenges in long-term continuous operation, and the high capital and operating costs associated with large-scale systems [218]. Therefore, although plasma treatment can outperform conventional pyrolysis or gasification in selected aspects such as tar destruction, pollutant control, and syngas cleanliness, it cannot yet be regarded as a universally superior option for all organic solid waste treatment scenarios [219].

The typical process flow of plasma treatment is illustrated in Figure 3. Based on the methods of plasma generation and the design of plasma reactors, various types of plasma gasification technologies exist (Table 4), each with its own distinct characteristics, advantages, and disadvantages. The selection of these different types of plasma gasification technologies in practical applications should be comprehensively evaluated based on factors such as the type of waste, treatment scale, energy efficiency requirements, and economic feasibility [220].

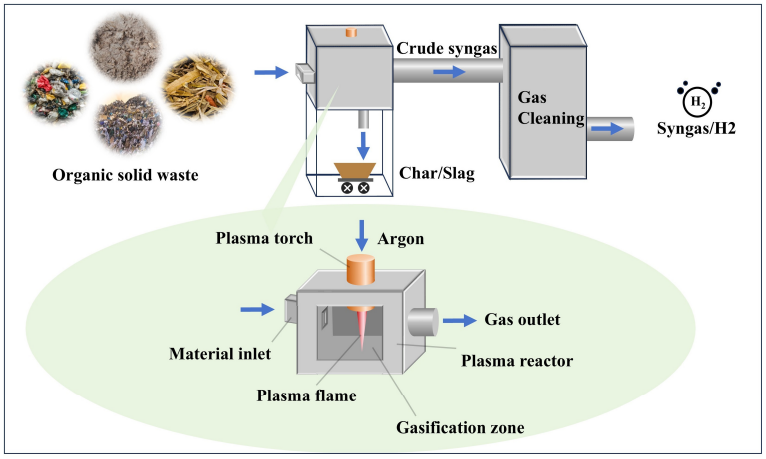


Figure 3. Organic waste plasma treatment process.

Compared with conventional pyrolysis and gasification technologies, plasma technology can operate at relatively low oxygen concentrations, achieving more complete decomposition of waste while reducing the formation of by-products such as tar. It offers higher pyrolysis rates and lower emissions of harmful gases. Its elevated temperatures and energy densities enable the treatment of a wider range of waste types, including biomass, rubber waste, and plastics. Due to its efficiency and environmental friendliness in pro-

cessing organic waste, plasma technology has become one of the important methods for waste valorization.

Table 4. Comparison of direct current (DC), alternating current (AC), radio frequency (RF), and microwave plasma methods.

Types of Gasification	Temperature	Mode of Plasma Generation	Characteristics	Advantages	Disadvantages	Ref.
DC Plasma	5000–20,000 K	Stable DC Arc Discharge	High-temperature plasma is generated using a DC arc, reaching temperatures exceeding 10,000 °C	High temperatures enable complete decomposition of waste, improving energy efficiency and the quality of syngas	High power consumption, and the equipment requires relatively high maintenance costs	[221,222]
AC Plasma	4000–10,000 K	AC High-Voltage Periodic Discharge	High-temperature plasma is generated using an AC arc, forming a plasma jet at the minimum gap between high-voltage electrodes.	Avoids localized overheating and corrosion of electrodes caused by unipolar continuous discharge, thereby extending equipment lifespan	Poor control precision, and variations in the electrodes can easily affect plasma stability	[223]
RF Plasma	3000–8000 K	Radiofrequency electron heating using electrodes	High-temperature plasma is generated using RF plasma, operating at a frequency of 13.56 MHz	High-temperature stability, capable of effectively treating various types of waste, with precise temperature control	High demands on electrodes, complex system configuration, and relatively low energy efficiency	[224]
Microwave Plasma	800–3500 K	Generated using a magnetron	High-temperature plasma is generated using microwave energy, with temperatures reaching several thousand degrees Celsius	Offers rapid heating and precise temperature control, suitable for small-scale and modular systems	Requires specialized equipment (e.g., microwave generators), resulting in higher costs for large-scale waste treatment	[225]

4.2.1. Plasma Gasification of Biomass Waste

Due to its ability to generate a high plasma density, plasma gasification is considered a promising technology for producing syngas from biomass. Compared with conventional biomass gasification, plasma gasification can be regarded as an intensified gasification route because the plasma zone provides extremely high local temperatures and energy densities, which enhance tar cracking, char conversion, and the formation of cleaner syngas from low-quality or heterogeneous biomass feedstocks [215]. The main advantages of plasma gasification include better control over syngas composition and a significant reduction in tar, carbon dioxide, and hydrocarbon contents [226]. Recent technical evaluations further show that these advantages can be reflected in key performance indicators. For example, steam plasma entrained-flow gasification was reported to increase the H_2/CO ratio to 1.03, more than double that of oxygen-blown entrained-flow gasification, while simultaneously improving the carbon conversion efficiency to 95% and reducing syngas CO_2 content by 79%. The same study also reported a cold gas efficiency of about 80% and plasma power conversion efficiencies above 85%, indicating that plasma assistance can improve both syn-gas quality and carbon utilization under optimized steam-plasma conditions [215].

The choice of carrier gas can influence the conversion efficiency of biomass and the properties of the final products. Common carrier gases include hydrogen, nitrogen, oxygen, and carbon dioxide, each playing a different role in plasma reactions [227]. In practice, steam is particularly important because it promotes water–gas and steam-reforming reactions, which are favorable for hydrogen-rich syngas generation, whereas nitrogen or air

tends to dilute the product gas and reduce syngas calorific quality [228]. When hydrogen is used as the carrier gas, hemicellulose and lignin predominantly generate CO_2 and C_2H_2, respectively. In contrast, nitrogen plasma pyrolysis of biomass mainly produces gaseous products (primarily H_2 and CO_2, accounting for more than 90% of the total gas volume) and solid char [229], with no formation of liquid tar. When water vapor is introduced during the reaction, the following reactions occur [230]:

$$C + H_2O \rightarrow CO + H_2$$

$$CO + H_2O \rightarrow CO_2 + H_2$$

The results indicated that the yields of hydrogen and carbon dioxide increased, while the yield of carbon monoxide decreased.

Temperature variation was found to significantly influence the conversion efficiency of biomass [231]. Muvhiiwa et al. investigated the nitrogen plasma pyrolysis of wood pellets within the temperature range of 673.15–1273.15 K, during which the pellets were converted into gaseous products and residual char. Their findings revealed that temperatures above 1073 K favored the production of gaseous products, whereas temperatures below this threshold were more conducive to the formation of char and pyrolytic oil with limited amounts of syngas [149]. Similar temperature-dependent behavior has also been reported in plasma gasification studies of waste-derived biomass-like feedstocks: when the plasma gasification temperature increased from 1100 °C to 1300 °C, H_2 yield increased from 41.5 mol/kg to 69.8 mol/kg, while CH_4 and CO_2 yields decreased markedly, confirming that elevated plasma temperatures shift the system toward lighter and more hydrogen-rich gaseous products [232].This trend reflects the enhanced contribution of steam gasification and water–gas shift reactions in plasma systems, which is also why steam plasma configurations are often preferred when hydrogen-rich syngas is the target product [233].

Therefore, plasma gasification of biomass shows a clear comparative advantage over conventional gasification in tar destruction, hydrogen-oriented syngas upgrading, and carbon conversion under suitable operating conditions [234]. In addition, recent reviews emphasize that although plasma gasification can improve syngas cleanliness and feedstock flexibility, its commercial deployment for biomass remains constrained by scale-up challenges, long-term continuous operation, and the need for detailed economic evaluation [216].

4.2.2. Plasma Treatment and Valorization of Waste Rubber

Waste tires are composed of natural rubber, synthetic polymers, textiles, fillers (e.g., carbon black and silica), steel, and various additives [235]. Waste rubber possesses a stable covalently cross-linked network [236,237], and this complex structure restricts the mobility of rubber polymer chains, thereby hindering its recyclability. In addition, waste tires have relatively high calorific values, typically in the range of 35–45 MJ/kg, which makes them both difficult wastes and potentially valuable thermochemical feedstocks [238]. In recent years, various approaches have been explored, including ultrasonic [239], thermochemical [240], and microbial methods [241]. Plasma treatment can break the internal cross-linked network structure of rubber, weakening the intermolecular forces between rubber molecules [242]. Therefore, plasma treatment of waste rubber can be understood as a specialized intensified thermochemical route because it combines high-energy decomposition with devulcanization of the cross-linked rubber structure that limits conventional mechanical recycling [242]. During the treatment of waste rubber using plasma technology, no liquid products are generated. Waste rubber can be converted into valuable gases, and the resulting solid residues exhibit a structure and surface area nearly comparable

to commercial carbon black [243]. This product pattern differs from many conventional waste-tire pyrolysis systems, which commonly produce oil together with gas and char, and therefore suggests that plasma treatment is particularly suitable for gas-and-solid-oriented valorization rather than liquid-fuel recovery [244].

Plasma technology can also effectively prevent high sulfur content in the gaseous products. Studies have shown that no sulfur dioxide was detected in the gas produced by plasma pyrolysis [245]. Under conditions of high-power input and in the presence of dolomite, sulfur can be reduced in the gas phase and collected together with the solid residues in the form of non-volatile sulfides and elemental sulfur, resulting in only trace amounts of sulfur in the gas products, with no sulfur dioxide observed [246]. This sulfur-retention behavior is particularly important because sulfur removal is one of the major practical barriers in the thermochemical utilization of waste tires, and the suppression of SO_2 formation represents a clear environmental advantage of plasma treatment over less controlled thermochemical routes [246].

Waste-tire plasma treatment remains a relatively specialized route, and its wider practical deployment is still limited by high electricity demand, plasma reactor and electrode durability, process integration complexity, and the need to balance gas quality, sulfur control, and carbon black recovery within a single process [247,248]. Therefore, plasma treatment of waste rubber is best regarded as a niche but promising valorization strategy when clean gas production and high-value solid carbon recovery are prioritized, rather than as a universal replacement for conventional waste-tire pyrolysis or gasification technologies [249,250].

4.2.3. Plasma Conversion of Plastic Waste

The non-degradability of plastic materials poses environmental hazards [251]. Compared with conventional pyrolysis and gasification, plasma conversion of plastic waste can be understood as an intensified thermochemical route, because the highly energetic plasma environment enables rapid bond cleavage, strong tar suppression, and direct conversion of mixed plastics into gas-rich products even under oxygen-starved conditions [184]. Plasma conversion of plastic waste can be understood as an intensified thermochemical route, because the highly energetic plasma environment enables rapid bond cleavage, strong tar suppression, and direct conversion of mixed plastics into gas-rich products even under oxygen-starved conditions [252].

When plastic waste particles are introduced into a plasma reactor, volatile compounds are rapidly released and undergo further cracking and reforming reactions. The gaseous products generally include H_2, CO, CH_4, acetylene, and other light hydrocarbons, and the highly energetic plasma environment can promote hydrogen-forming reactions while suppressing the accumulation of heavier condensable intermediates [253]. Tang et al. found that under optimal experimental conditions, the hydrogen concentration in the gas products could reach 18%, and the acetylene concentration could reach 5%. After introducing steam injection, the combined content of hydrogen and carbon monoxide in the gaseous products could reach 40%, while the acetylene concentration decreased only slightly, achieving a 96% solid conversion rate and a gas yield of 2160 mL/g [254]. These results indicate that plasma conversion can substantially improve oriented toward gasification plastic valorization, particularly when hydrogen-rich or syngas-rich gas streams are the target products. Mohsenian et al. found that when the arc current ranged from 80 to 140 A and the arc temperature ranged from 11,022 to 16,343 K, the concentration of H_2 in the products increased with increasing arc current and temperature. Using acrylonitrile–butadiene–styrene copolymer as a modifier, carbon black nanospheres were prepared. As the arc current increased, the formation of hydrocarbons decreased, while

the production of H_2 increased [222]. This result suggests that plasma operating intensity can shift product selectivity from high-carbon-content gas toward more hydrogen-rich gas, while also enabling the simultaneous recovery of nanostructured carbon materials [222].

Plasma conversion of plastic waste is generally best suited for mixed, contaminated, or difficult to recycle plastics where complete breakdown or gas-oriented valorization is desired, whereas its wider practical deployment remains limited by high electricity demand, reactor complexity, and the requirement that the recovered gas or carbon product must have sufficient value to justify the energy input [255].

Plasma gasification can offer environmental advantages over incineration, mainly because cleaner syngas production and vitrified slag formation can reduce landfill dependence, greenhouse gas emissions, and heavy metal leaching potential [247]. For example, a recent quantitative review found that plasma gasification generally outperforms landfilling and incineration in several life-cycle impact categories, and that the lower human-toxicity potential of plasma gasification is largely attributed to the formation of vitrified slag, which can usually be landfilled or reused with minimal leaching, unlike the more hazardous ash from conventional gasification or incineration [256]. The cleaner syngas production can improve downstream energy recovery, so that for the same amount of useful energy produced, the overall environmental burden may be reduced relative to less advanced waste-treatment routes [247]. Economic evidence shows a more mixed picture: one recent review reported that a plasma arc gasifier could generate about 816 kWh per tonne of MSW, equivalent to about US $77.36 of electricity per tonne of waste, but the same source also noted that the investment recovery period may still reach 18 years because of the high installation, operation, and maintenance costs of plasma systems [257]. For example, under a comparative framework for a 500 t MSW/day plant, plasma gasification achieved about 90 wt.% mass reduction and generated only about 0.18 t residue per ton of waste, while also showing very low dioxin/furan emissions (<0.00925 μg/Nm^3) [258]. Economic assessment, however, shows a more mixed picture, because plasma gasification required higher capital investment (US $101 million) and annual operation and maintenance costs (US $8.5 million/year) than pyrolysis and conventional gasification, despite its higher net energy production potential (816 kWh/t MSW) [259]. Plasma gasification has only moderate-to-high technology maturity and still faces limited commercialization compared with conventional pyrolysis and gasification [248]. Overall, existing TEA, LCA, and life-cycle-thinking evidence suggests that plasma treatment is a promising but highly context-dependent route whose practical viability depends on system scale, feedstock homogeneity, electricity price, process integration, coproduct utilization, and local policy conditions [248].

4.3. SCWG Technology

SCWG utilizes supercritical water as both the reaction medium and reactant. Due to the unique properties of water above its critical point (T > 374 °C, P > 22.1 MPa), feedstocks can be directly converted into hydrogen-rich gases [260]. Compared with conventional gasification, its main advantage lies in the ability to directly process wet feedstocks without the energy-intensive drying step that is usually required before thermochemical conversion [261].

The low viscosity and dielectric constant of supercritical water facilitate the dissolution of organics and gases [262,263]. This property allows gasification reactions to occur in a homogeneous phase, reducing mass transfer resistance and significantly enhancing reaction rates [264]. Shen et al. investigated an energy sustainable disposal system to improve the energy use efficiency in supercritical water gasification process by integrating syngas combustion, waste heat recovery, and the production of multi-energy products at multiple

energy grades (e.g., hydrogen, heat, and electricity) at the optimal operating conditions of gasification temperature of 550 °C, pressure of 23 MPa, and feed concentration of 5% (Figure 4) [132]. However, SCWG still faces important engineering and economic challenges, including high-pressure reactor requirements, corrosion, char formation, salt precipitation, plugging, and the high capital and operating costs associated with supercritical operation. Therefore, the practical viability of SCWG depends not only on its ability to eliminate drying, but also on feedstock composition, reactor stability, heat integration, catalyst choice, and the management of solids and salts under supercritical conditions [265].

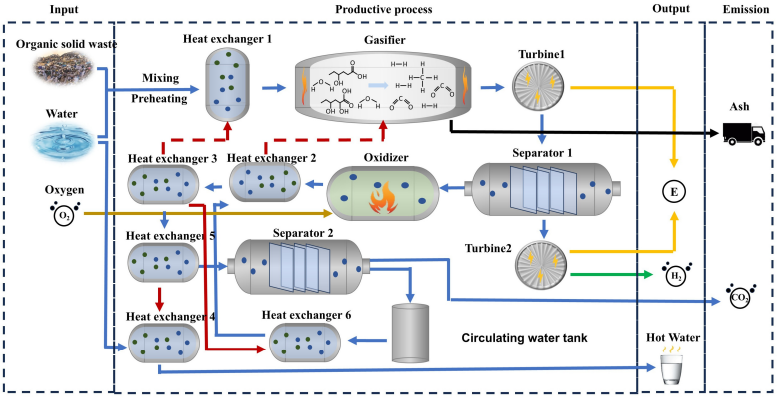


Figure 4. Process flow diagram of a hydrogen self-sufficient treatment system for plastic waste using SCWG.

4.3.1. SCWG of Biomass Waste

Biomass gasification can convert biomass into syngas, a mixture of H_2 and CO, suitable for power generation or downstream catalytic synthesis to produce hydrocarbons ranging from methanol, ethanol, and dimethyl ether to green diesel and aviation fuels [266,267]. Conventional biomass gasification in air/oxygen or steam requires an initial pre-drying step to ensure that the moisture content is below 10–15% prior to gasification [268].

This requirement is a major limitation for wet biomass, because real biomass feedstocks may contain up to about 80 wt% water, and the introduction of a drying step can potentially make the process economically unattractive. In contrast, SCWG, as a specialized for wet feedstocks gasification technology, eliminates the need for the pre-drying step required in conventional processes. Under supercritical conditions, biomass macromolecules undergo hydrolysis to form corresponding monomers, which then participate in a series of chemical reactions that convert them into gaseous products, including H_2, CO_2, CO, CH_4, and other short-chain hydrocarbons [269]. As a result, the syngas produced through SCWG typically contains a higher proportion of H_2, while the contents of CO, tar, and char are significantly reduced, all without relying on energy-intensive pre-drying operations [270].

Operational parameters such as reaction temperature, residence time, feedstock-to-water ratio, and operating pressure all influence the SCWG of biomass [271,272]. For example, Lu et al. found that reaction temperature had the most significant impact, with higher temperatures markedly enhancing carbon gasification efficiency and hydrogen production [273]. Similarly, Azargohar et al. observed that the yield of gasification products increased with temperature when gasifying rapeseed hull fuel particles. When the temperature increased from 350 °C to 650 °C, the hydrogen yield from corn starch rose from 0.4 mmol/g to 3.17 mmol/g [274]. Among these parameters, temperature is generally regarded as the most important factor affecting gasification efficiency and hydrogen yield. The influence of pressure is generally less pronounced than that of temperature, but it is not negligible. In practical biomass SCWG experiments for hydrogen production, increasing pressure often has a beneficial effect on hydrogen yield; for example, the hydrogen yield of

wood sawdust increased from 15.2 to 17 mol/kg when the pressure rose from 17 to 30 MPa, and the hydrogen yield of cotton cocoon shell increased from 5.9 wt% to 12.6 wt% when the pressure increased from 23 to 48 MPa at 477 °C. Accordingly, the operating pressure for biomass SCWG is commonly considered to fall in the range of 22–30 MPa, balancing hydrogen-production performance and system cost [275,276].

In addition, catalysts can reduce thermal energy requirements and increase gas and hydrogen yields. Catalysts are generally divided into two groups: homogeneous and heterogeneous. Homogeneous catalysts typically enhance hydrogen production by promoting the water–gas shift reaction or facilitating C-C bond cleavage [277,278]. Among heterogeneous catalysts, Ni-based catalysts are widely regarded as particularly effective for biomass SCWG, while the addition of suitable supports or promoters can further improve hydrogen yield and catalyst stability [279]. However, catalyst deactivation caused by coking, poisoning, sintering, and leaching of active metals remains a major challenge during long-term operation [280]. Among heterogeneous catalysts, Ni-based catalysts are widely regarded as particularly effective for biomass SCWG, while the addition of suitable supports or promoters can further improve hydrogen yield and catalyst stability [279]. However, catalyst deactivation caused by coking, poisoning, sintering, and leaching of active metals remains a major challenge during long-term operation [281].

4.3.2. SCWG of Sewage Sludge

SCWG, with its ability to directly treat high-moisture-content organic matter under high temperature and pressure while avoiding the energy-intensive predrying step required by conventional thermochemical routes, provides a particularly suitable path-way for the resource-oriented conversion of sewage sludge [282,283].

Most existing studies therefore focus on improving hydrogen-rich gas production and gasification efficiency through catalyst addition and process optimization [284]. Khan et al. reported that the key parameters affecting H_2 yield in sewage-sludge SCWG were temperature, carbon content, hydrogen content, and pressure [285]. Hao et al. further found that increasing the mass fraction of supercritical water enhanced H_2 production while reducing CO yield, and suggested that the mass fraction of supercritical water should be maintained between 66% and 81% [286]. Sikarwar et al. employed a hybrid direct-current thermal plasma to treat sludge, producing syngas in a system containing waste CO_2. The H_2 yield reached approximately 0.5 m^3/kg of fuel, with a carbon conversion efficiency as high as 97% [287]. Wastewater sludge can achieve efficient gasification and promote hydrogen production even at relatively low temperatures, provided that a sufficient amount of catalyst is present. Hantoko et al. investigated the catalytic SCWG of wastewater sludge using activated carbon [288]. They found that at a temperature of 400 °C, both hydrogen yield and carbon efficiency increased with higher catalyst loading. The introduction of metal or metal oxide catalysts significantly enhanced gasification efficiency and hydrogen selectivity while reducing liquid residues and tar byproducts. Similarly, Afif et al. reported that under conditions of 380 °C, a Raney nickel catalyst loading of 1.8 g/g, and a reaction time of 15 min, the carbon gasification rate increased from 10% without a catalyst to approximately 70%, and the hydrogen gasification rate increased from 4% to 113% [289].

In addition to gas production, SCWG has shown value in the stabilization of in-organic contaminants in sewage sludge, because most metal elements such as Zn, Pb, and Cu can be transferred into the solid residues under supercritical conditions, which is beneficial for subsequent solid-residue reduction and stabilized disposal [290]. However, sewage sludge SCWG still faces major engineering and economic challenges, including high-pressure reactor requirements, corrosion, salt precipitation, plugging, catalyst deactivation, and the high capital and operating costs associated with super-critical operation [265]. However,

these advantages should not be interpreted as unconditional superiority. Sewage sludge SCWG still faces major engineering and economic challenges, including high-pressure reactor requirements, corrosion, salt precipitation, plugging, catalyst deactivation, and the high capital and operating costs associated with supercritical operation [291,292].

4.3.3. SCWG of Food Waste

In municipal solid waste, food waste accounts for the largest proportion (54.2–65.9%) and is typically characterized by high moisture content and low calorific value, which makes conventional dry thermochemical conversion less favorable and complicates direct disposal [293]. The main organic components of food waste are carbohydrates, proteins, lipids, and plant-derived fibrous matter, which together make it a potentially valuable feedstock for hydrogen-rich gas production. Utilizing SCWG to convert food waste into hydrogen-rich syngas represents a clean, efficient, and resource-recovering approach for food waste management [294].

Current studies on food-waste SCWG mainly focus on improving gasification efficiency and hydrogen production. Nanda et al. reported that higher reaction temperatures enhanced gasification efficiency and syngas production from food waste [295]. More specifically, Su et al. found that the hydrogen yield of unsorted food waste increased by 85.3%, from 2.9 to 5.4 mol/kg biomass, when the reaction temperature increased from 420 to 480 °C at 30 min, 5 wt% feed concentration, and 23–28 MPa [296]. The same study also showed that, at 480 °C and 28 MPa with 5 wt% feed concentration, extending the residence time from 30 min to 45 min further increased the hydrogen yield from 5.4 to 6.5 mol/kg. Catalyst development has also attracted increasing attention in food-waste SCWG because catalytic assistance can substantially improve hydrogen selectivity and gasification efficiency. For example, one study reported that NaOH showed the best catalytic performance for food waste SCWG, achieving a maximum hydrogen yield of 12.73 mol/kg, which was much higher than the non-catalytic value of 2.0 mol/kg under the same comparison framework [296]. In addition, La-modified Ni/Al_2O_3 catalysts have also shown promising activity. A recent catalyst screening study reported that Ni/Al_2O_3 with 9 wt% La loading was the most effective formulation, increasing the hydrogen yield to 5.6 mol/kg biomass, compared with 4.1 mol/kg for unmodified Ni/Al_2O_3 [297].

The practical application of food-waste SCWG still depends strongly on feed heterogeneity, residence-time control, catalyst durability, and the management of salts and solid residues under supercritical conditions [291]. The practical application of food-waste SCWG still depends strongly on feed heterogeneity, residence-time control, catalyst durability, and the management of salts and solid residues under supercritical conditions [296]. Therefore, food-waste SCWG is understood as a promising for wet feedstocks conversion route for hydrogen-rich syngas production, whose practical viability depends on process optimization, catalyst stability, and upstream feedstock management rather than on the supercritical process alone [298].

Existing evidence suggests that the environmental and economic performance of SCWG remains highly feedstock- and system-dependent rather than uniformly favorable [299]. A recent life-cycle study of SCWG for biomass fermentation residue, using the operation stage as the system boundary and 1 ton of SSF residue as the functional unit, reported a global warming potential of −216.6 kg CO_2–eq/FU and an acidification potential of −8.9 kg SO_2–eq/FU, indicating that SCWG can be environmentally beneficial under optimized conditions [300]. From an economic perspective, currently available evidence is still relatively preliminary, but the catalytic SCWG at 400 °C is theoretically more economically feasible than non-catalytic SCWG at 600 °C because the lower-temperature route reduces utility, capital, and operating costs [299]. Overall, existing LCA and economic

studies support SCWG as a promising route for wet feedstock valorization, but its practical viability still depends strongly on reaction temperature, feed concentration, catalyst strategy, reactor design, and the availability of more harmonized full-system environmental and techno-economic assessments [300].

4.4. FJH Technology

FJH is a technology that utilizes the Joule effect to rapidly convert electrical energy into heat. The principle of the technology is that under the action of high-power, short-duration electrical impulses from a power source, the material is rapidly heated to high temperatures (up to 3000 K or higher) within milliseconds, which is conducive to the effective decomposition of complex structures and facilitates the reorganization of carbon atoms into orderly configurations [301,302]. Most of the heat is released in the form of radiation from the blackbody system along with bright light, so the resulting product is named "flash graphene" (FG) [303,304]. The experimental setup for graphene preparation via FJH mainly consists of a capacitor (e.g., a metallic, ionic, or semiconducting conductor) and an insulating tube. The insulating tube covers both ends of the container, while FJH electrodes made of brass or graphite are mounted at the tube ends (Figure 5) [305].

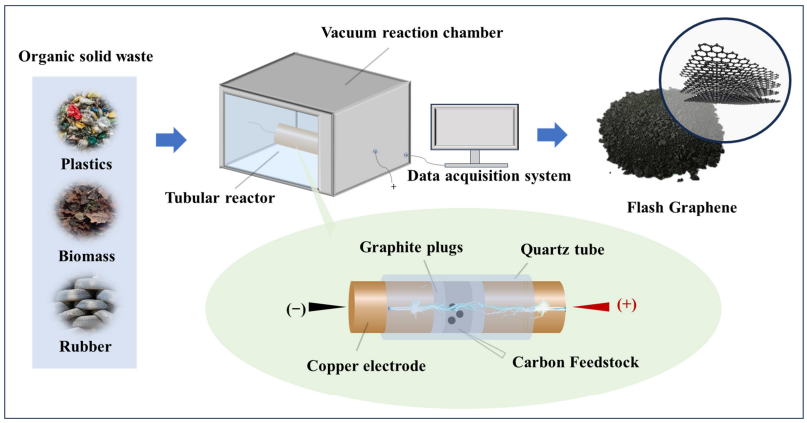


Figure 5. Process flow diagram for the preparation of graphene by FJH.

Graphene, as an emerging nanomaterial, possesses unique physical and chemical properties that endow it with enormous application potential across a wide range of fields. Rapid large-scale production of graphene, as well as the regeneration of graphene from wastes with high carbon content, has become an important research direction. The FJH technique was not originally proposed for solid waste valorization, but rather as a rapid heating and material synthesis method in advanced materials research. However, studies have demonstrated that selected high-carbon-content organic solid wastes can serve as suitable precursors for graphene or graphitic carbon production through the FJH process [306]. The underlying reason for this phenomenon lies in the carbon content and electrical properties of organic solid wastes [136]. Therefore, in the context of organic solid waste management, FJH should be regarded primarily as a high-value carbon material upgrading route for selected high-carbon-content and electrically suitable precursors.

4.4.1. Carbon Content

Carbon content is the primary factor determining the graphene yield during the FJH process applied to organic solid wastes [304]. Previous studies have demonstrated that organic solid wastes are typically rich in organic matter and contain relatively high proportions of carbon. Specifically, the carbon content in biomass wastes is approximately 40 wt% [307], whereas plastic wastes derived from major commercial plastics exhibit carbon

contents ranging from 60 to 90 wt% [308]. Similarly, the carbon content of food residues, wood wastes, paper, textiles, and rubber has been reported to be in the ranges of 30–50 wt%, 40–50 wt%, 45 wt%, 45–60 wt%, and up to 90 wt%, respectively [309].

Only precursors with high carbon content or easily graphitizable components (e.g., carbon black, calcined coke, and anthracite) can be successfully converted into high-quality graphene structures under the extreme heating (>3000 K) and rapid quenching conditions of FJH [310]. Such high-carbon precursors can rapidly eliminate non-carbon elements at elevated temperatures, thereby reducing impurities and facilitating the formation of graphene layers [137]. In particular, when high-carbon-content feedstocks are used, graphene yields can reach 80–90%, with carbon purities exceeding 99%. In contrast, low-carbon-content or non-graphitizable carbon sources (e.g., coffee grounds) fail to form ideal graphene structures under the same conditions, resulting in lower product quality and structure, with yields of only around 35%. To enable low-carbon-content feedstocks to produce high-quality graphene via FJH, it is typically necessary to introduce highly conductive additives (e.g., carbon black) to enhance conversion efficiency. Notably, under conditions with 5% carbon black added to improve electrical conductivity, coffee grounds can achieve a carbon conversion rate of approximately 85% through the FJH process, yielding high-quality FG [306].

4.4.2. Electrical Properties

In practical operation, due to the resistive heating nature of the FJH process, the intrinsic electrical resistivity of the sample directly affects the efficiency of current conduction and heat generation, which in turn determines whether the reaction system can reach the desired instantaneous high temperature (>3000 K). According to Ohm's law ($V/R = I$) and Joule's law ($P = I_2R$), if the sample's resistance is too high, the current may be insufficient, resulting in inadequate power delivery. Conversely, if the sample's resistance is too low, the current may short-circuit through the system, leading to insufficient heating within the sample itself, with most of the energy dissipated in the FJH apparatus rather than the material. Therefore, the sample resistance must fall within an appropriate range to maximize the electrical energy delivered. Since resistivity is an intrinsic property of the material, this requirement can limit the types of feedstock that can be used. To overcome this limitation, several techniques have been developed for non-conductive materials.

Firstly, a low-power preheating step can carbonize the feedstock, thereby improving its electrical conductivity. This approach is particularly useful when using plastics or biomass as raw materials. Currently, a two-step FJH strategy has been developed for converting waste plastics into graphene. In this two-step method, a prolonged, low-current discharge carbonizes the carbonaceous feedstock, increasing its conductivity and facilitating the removal of volatile compounds [311]. During the low-current FJH process of plastics, hydrocarbon volatiles are generated, including a significant amount of H_2 gas. High H_2 yields are observed regardless of the plastic type, with lower initial sample resistance leading to more complete hydrocarbon decomposition, thereby producing higher yields of H_2 and flash graphene [312]. This demonstrates that FJH also serves as a catalyst-free method for producing clean H_2 from mixed plastic waste.

Secondly, 10–20 wt% of conductive additives such as carbon black, tire carbon black, charcoal, or coal can be introduced to reduce the sample resistance below 10 Ω, enabling synchronous heating of non-conductive materials. Luong et al. also reported that the additive approach can adjust the contact resistance between carbon sources, allowing precise control over temperature and heating duration, thereby improving the quality of the resulting graphene [136].

After examining the application characteristics of each emerging technology, it is essential to identify the optimal combinations between waste types and treatment routes. Table 4 summarizes the technology pathways suitable for different types of organic waste, including their corresponding traditional and emerging technologies, advantages, and potential products. This summary provides a comprehensive reference for selecting appropriate treatment strategies.

More importantly, the main strength of FJH lies in high-value valorization rather than in serving as a primary treatment route for bulk solid wastes. In the context of organic waste management, FJH should therefore be regarded primarily as a carbon material upgrading route for selected precursors with high carbon content and suitable electrical properties [137]. These constraints indicate that FJH is applicable only to a limited range of wastes with high carbon content and electrical compatibility, and in many cases requires pretreatment or conductive additives before effective conversion can be achieved [136]. Although FJH shows strong promise for the synthesis of graphene and other high-value carbon materials, its wider deployment in waste valorization is still constrained by feedstock conductivity requirements and the limited maturity of continuous processing systems [313].

Overall, these advanced and enhanced technologies are not superior to traditional technologies in all aspects, but rather exhibit more prominent advantages in specific performance indicators and application scenarios. MAP, plasma gasification, SCWG, and FJH show potential to outperform traditional routes in heating enhancement, pollutant control, wet material conversion, and high-value carbon material preparation, respectively [314]. However, these advantages are usually accompanied by higher equipment complexity, lower technological maturity, or higher capital costs [248]. Therefore, these technologies are more suitable as supplements and enhancements to traditional technologies and are expected to play an important role in the high-value utilization of organic waste in the future. The detailed results are shown in Table 5.

Table 5. Technology pathways suitable for different types of organic waste and their main products.

Types of Organic Waste	Traditional Technologies	Advanced and Intensified Technologies	Advantages	Optimal/Combined Pathways	Potential Products	Ref.
Sludge	AD, incineration, HTC, composting	MAP, SCWG	Suitable for high moisture content waste; energy and resource recovery	HTC + SCWG	Hydrochar, clean syngas, hydrogen-rich gas	[56]
Food waste	AD, composting, HTC	SCWG	Suitable for wet and readily biodegradable waste	HTC + SCWG	Hydrogen-rich gas, fuel gas, hydrochar	[296,315]
Livestock manure	AD, composting, HTC, incineration	SCWG	Suitable for nutrient recovery and wet waste stabilization	AD + composting/ HTC + AD	Biogas, digestate fertilizer, hydrochar	[100]
Agricultural residues, lignocellulosic biomass	Pyrolysis, gasification, incineration, composting	FJH, MAP	Suitable for dry carbon rich feedstocks; energy recovery and high value utilization	Pyrolysis + FJH	Biochar, graphene, functional carbon materials	[42]
Plastics, polymer waste	Pyrolysis, incineration, gasification	Plasma gasification, FJH	Suitable for carbon rich feedstocks; high value material recovery	Pyrolysis + FJH/Plasma gasification	Syngas, graphene, functional carbon materials	[181,311]

5. Coupling Pathways Between Conventional and Emerging Technologies

In recent years, the integration of multiple advanced processes for coupled treatment has emerged as a key research direction in the resource recovery of organic waste. Coupled

technologies such as pyrolysis–gasification integration, pyrolysis and plasma coupling, and the integration of thermal and biological treatment offer high energy conversion efficiency, low pollutant emissions, broad feedstock adaptability, and strong operational flexibility. Compared with single treatment pathways, coupled technologies can achieve deep conversion of organic components and targeted production of high-value products through process synergy, energy complementarity, or functional enhancement, thereby significantly improving overall system efficiency and resource recovery. These approaches have become crucial technical supports for achieving efficient treatment and multi-level resource utilization of organic waste.

5.1. Pyrolysis–Plasma Coupling Technology

Pyrolysis–plasma coupling technology has recently emerged as a multienergy-field synergistic enhancement approach in the treatment of organic wastes (Figure 6). Its core concept is to integrate conventional pyrolysis with high-temperature plasma processing, achieving synergistic optimization of deep organic decomposition and pollutant control through staged reactions and gas recirculation mechanisms. The performance improvement does not arise solely from the increase in temperature. Instead, it results from the staged mechanism: in the first stage, pyrolysis converts solid waste into more mobile intermediates such as tar, light hydrocarbons, and oxygenated volatiles; in the subsequent stage, the plasma utilizes high-energy electrons, reactive radicals, and an ultra-high-temperature environment to further drive these intermediates along pathways of deep cracking, steam reforming, and dechlorination/deoxygenation [316]. This technology typically employs a "two-stage process structure": initially, feedstock is thermally decomposed in the pyrolysis unit to produce char, pyrolysis oil, and pyrolysis gas; subsequently, the pyrolysis gas enters the plasma reaction zone, where under ultra-high-temperature plasma conditions, complex organic intermediates such as tars, aromatics, and chlorinated hydrocarbons are further cracked, yielding cleaner synthesis gas with higher calorific value, primarily composed of H_2 and CO [317–319].

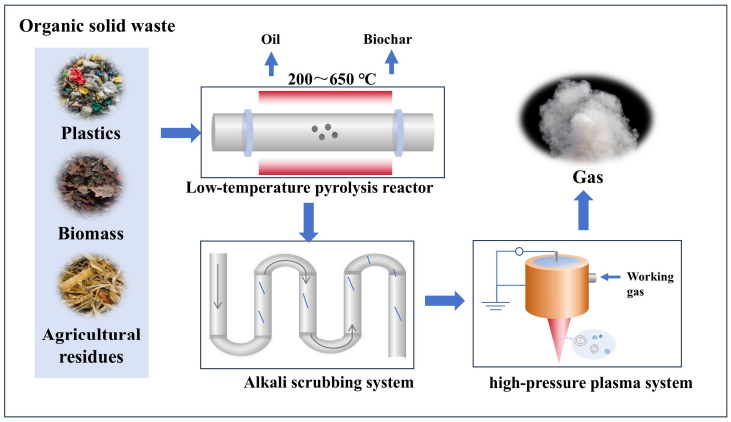


Figure 6. Process flow of low-temperature pyrolysis coupled with high-pressure plasma technology.

This coupled system combines the energy efficiency advantages of pyrolysis with the strong redox capability of plasma, significantly reducing the residual tar and pollutants that are difficult to fully decompose during pyrolysis, while avoiding the stress on reactor lifespan and energy consumption associated with single-stage high-temperature treatment. The two-stage design allows flexible control of process parameters and optimization of syngas composition [320]. Compared with standalone pyrolysis, the pyrolysis–plasma coupled process can increase tar removal rates to approximately 90%, raise H_2 content in the syngas by 20–40%, and significantly reduce the emissions of chlorinated compounds,

NO_x, and toxic dioxins [321,322]. Because the flow rate and composition of pyrolysis volatiles from the upstream unit vary with feedstock fluctuations, the downstream plasma zone is highly sensitive to discharge power, residence time, and gas composition. Therefore, dynamic matching and real-time control between the two reaction zones are key issues in scale-up design. In addition, plasma systems still face practical constraints, including high electricity demand, limited lifetimes of plasma torches and refractory materials, and high capital costs. Consequently, although this technology outperforms standalone pyrolysis in terms of gas upgrading and pollution control, its industrial deployment still depends on further optimization of reactor design and process control [214].

5.2. HTC-SCWG Coupling Technology

HTC and SCWG, as typical wet thermochemical conversion technologies, each demonstrate distinct advantages in the treatment of high-moisture-content organic wastes [323]. HTC, under moderate temperatures and pressures, can convert organic wastes with high moisture content (e.g., sewage sludge, food waste, and agricultural or forestry residues) into high-carbon-content hydrochar, a liquid phase enriched with small organic molecules, and a minor gas fraction. This process is characterized by low energy consumption, mild reaction conditions, and broad feedstock adaptability. SCWG, in contrast, operates under supercritical conditions (T > 374 °C, P > 22.1 MPa) and efficiently decomposes organic matter into syngas primarily composed of H_2 and CO, making it suitable for high-value energy recovery and clean fuel production [324]. The key to the performance improvement after coupling lies in the fact that HTC first converts complex wet waste into more controllable solid–liquid products through reactions such as hydrolysis, dehydration, and decarboxylation.

Specifically, when used as a pretreatment stage, HTC not only reduces feedstock moisture content and chemical stability but also enriches carbon in the solid hydrochar fraction while transferring part of the soluble organics into the liquid phase, thereby facilitating efficient conversion in the subsequent SCWG process (Figure 7). As a result, the subsequent SCWG process deals with intermediates that have simpler chemical structures and higher reactivity. The process water generated from HTC becomes a highly reactive liquid-phase intermediate for downstream SCWG. The small organic molecules enriched in this liquid phase are generally more reactive in supercritical water than the original solid biomass and can more readily participate in homogeneous reforming and water–gas shift reactions [325]. Owing to its porous structure and abundant oxygen-containing functional groups, hydrochar exhibits higher gasification reactivity under SCWG conditions than raw biomass, leading to significantly enhanced H_2 yields and carbon conversion efficiency. Overall, this integrated system better follows the principle of cascade energy utilization than directly feeding raw feedstocks with high moisture content into supercritical gasification. For instance, Yan et al. prepared hydrochar from food waste and subjected the process water obtained after high-temperature carbonization to SCWG. The results indicated that the integration of HTC with SCWG could enable solid waste-to-energy conversion while mitigating issues such as reactor clogging, low carbon efficiency, and the treatment challenges of organics-rich HTC wastewater [326]. Therefore, coupling the two technologies offers the potential for synergistic process optimization and cascade resource utilization [327]. However, challenges such as corrosion, salt precipitation, clogging, and catalyst deactivation during long-term SCWG operation are not eliminated by upstream HTC. Therefore, the industrial feasibility of this coupled system still strongly depends on high-pressure reactor design and real-time process control.

In addition, the two-stage energy recovery process combining HTC and SCWG can also be applied to the treatment of household food waste. In this integrated process, food

waste is first subjected to HTC to obtain a derived liquid, which is then converted via SCWG into H_2-rich syngas, achieving an H_2 selectivity of 192.44% [315].

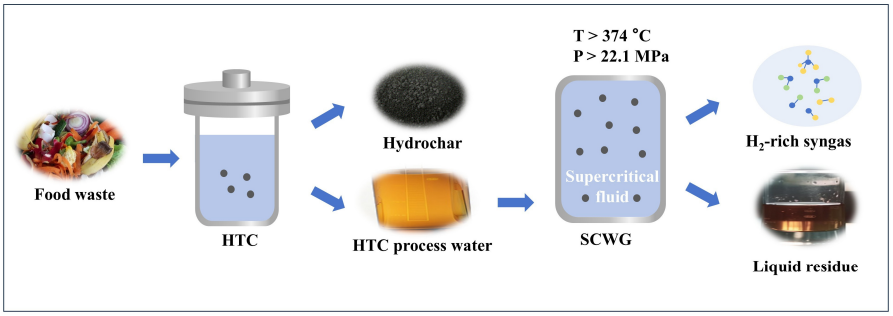


Figure 7. Cascade treatment of food waste combining HTC and supercritical SCWG.

5.3. Pyrolysis and FJH Coupling Technology

Conventional pyrolysis technology is widely employed for the thermochemical conversion of plastics, biomass, and composite wastes. This process primarily involves medium-temperature heating (300–700 °C) to decompose feedstocks, yielding gaseous products, liquid tars, and carbonaceous solid residues [328]. However, pyrolysis often suffers from limitations such as low graphitization degree of the carbonaceous products and high content of tar byproducts, which restrict its potential for high-value applications [329]. In recent years, the introduction of FJH technology has provided a novel pathway for the advanced utilization of pyrolysis products [330].

FJH has been extensively applied to instantaneously convert high-carbon-content feedstocks into highly crystalline graphene, graphitic carbon, or functional carbon materials. The efficiency of the FJH process strongly depends on the carbon content and electrical conductivity of the precursor; feedstocks with low carbon content or dense structures typically result in reduced yields, insufficient crystallinity, and residual impurities. Consequently, researchers have proposed using conventional pyrolysis as a pretreatment step for FJH, effectively removing volatiles and impurities and providing an ideal precursor for the subsequent FJH process. Studies indicate that pyrolysis followed by FJH treatment can reduce energy loss during the FJH stage (Figure 8) [137]. Moreover, biochars produced at medium to high temperatures (750–900 °C) possess suitable electrical resistance, eliminating the need for conductive additives such as carbon black, while reducing carbon emissions by 80.1–86.1% compared with direct FJH. This sequential treatment enables the stable production of few-layer graphene with improved structural quality [137]. Lu et al. further compared untreated biomass with pyrolysis-pretreated biomass subjected to FJH and found that the latter exhibited significantly enhanced microporous structure, carbon layer ordering, and specific surface area (> 900 m^2/g), resulting in superior supercapacitor performance, with an approximate 40% increase in specific capacitance [137]. Because continuous feeding, continuous discharge, and continuous product collection systems are not yet mature, pyrolysis and FJH coupling are more suitable as a pathway for high-value material upgrading rather than as a direct replacement for conventional pyrolysis in bulk waste treatment.

In summary, FJH serves not only as an emerging high-temperature transient processing technology but also plays a crucial role in the structural tuning and functional transformation of pyrolysis products. Compared with conventional pyrolysis, FJH can achieve ultra-rapid heating within milliseconds, significantly enhancing material performance. Its synergistic coupling with pyrolysis leverages the advantages of pyrolysis in feedstock compatibility and initial carbonization, while greatly expanding the pathways for valorizing organic solid wastes into high-performance conductive materials, adsorbents,

and electrode materials for energy storage devices, demonstrating substantial research value and promising application prospects.

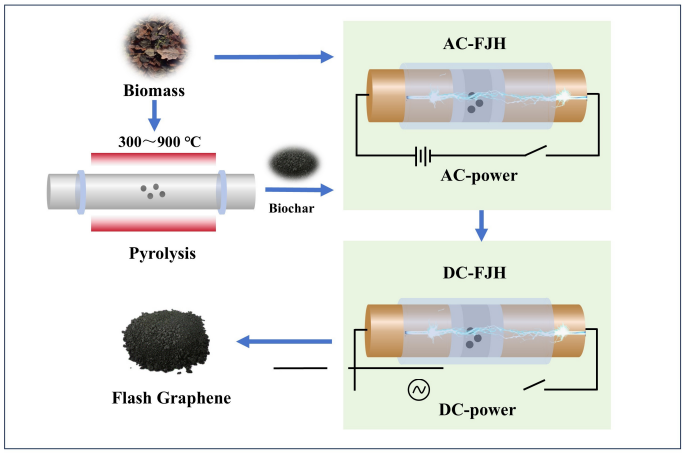


Figure 8. Pyrolysis and FJH coupling technology roadmap.

5.4. Microwave-Assisted Gasification Coupling Technology

Microwave heating is currently mainly applied in the field of biomass pyrolysis. However, due to its characteristics of instantaneity, uniformity, volumetric heating, and the ability to produce lightweight products, the coupling of MAP and gasification has attracted increasing attention. By integrating microwave heating with conventional gasification processes, this hybrid technology enables the efficient conversion of organic waste into high-quality syngas (Figure 9). The unique heating characteristics of microwaves accelerate the release of volatiles and the occurrence of pyrolytic reactions, thereby enhancing the gasification rate of biomass. Moreover, through precise temperature control, secondary reactions can be reduced, leading to simplified final products.

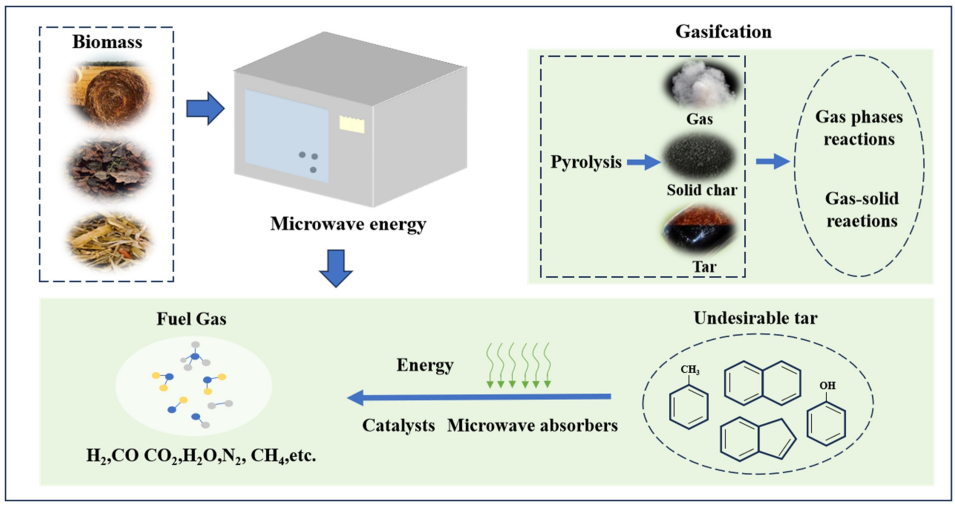


Figure 9. Process flow diagram of microwave-assisted gasification.

The influence of moisture content and feedstock pre-drying requirements on syngas characteristics has been evaluated in several studies. Wang et al. found that during the microwave pyrolysis of sewage sludge, higher moisture content increased the concentrations of H_2 and CO, and that CO generation tended to rise with increasing moisture when using microwave heating [331]. Integrating microwave energy with the gasification process allows continuous completion of drying, pyrolysis, and gasification within a single

reactor, producing syngas with higher H_2 and CO concentrations and significantly reducing tar formation [332]. MAP–gasification can improve gasification efficiency and direct the production of combustible gases, which can be further optimized through reactor design [333,334], process improvement, and the introduction of catalysts and/or microwave absorbers for catalytic selective gasification [335]. However, due to the limited microwave penetration depth and its strong dependence on the dielectric properties of the feedstock, it is difficult to maintain uniform heating behavior within the same reactor for materials with different moisture contents, ash contents, and compositions [336]. In addition, excessive local hotspots may lead to coking, localized melting, or catalyst deactivation. Therefore, electromagnetic reactor design, the configuration of microwave-absorbing materials, and power regulation are critical factors for ensuring stable continuous operation.

6. Conclusions

Conventional treatment technologies, including pyrolysis, composting, and anaerobic digestion, have reached a relatively high degree of engineering maturity in the treatment and resource recovery of organic wastes. However, their practical performance is still constrained by limited energy efficiency, incomplete pollutant control, and insufficient capacity for high-value product generation.

In contrast, advanced and intensified technologies for organic waste valorization, such as MAP, plasma gasification, SCWG, and FJH, provide new opportunities for improving energy conversion, pollutant destruction, and product upgrading. In particular, these technologies show distinctive potential for the treatment of feedstocks that are difficult to manage by conventional routes, including wastes with high moisture content, compositionally complex wastes, and residues with high carbon content intended for high-value material recovery. Nevertheless, their advantages are highly technology-specific and strongly dependent on feedstock characteristics, reactor design, operating conditions, and downstream processing requirements. At present, most of these technologies remain at laboratory or pilot scales, and their broader application is still limited by high capital cost, energy demand, reactor corrosion or durability issues, catalyst deactivation, scale-up difficulty, and uncertain technoeconomic feasibility.

From a future perspective, integrated and coupled pathways may further enhance the performance of advanced treatment systems by improving carbon conversion, broadening product portfolios, and reducing residual pollutants. Overall, the evidence reviewed in this work indicates that no single technology is universally optimal for all organic waste streams. Future research should therefore focus on improving the technoeconomic competitiveness of advanced and intensified technologies, strengthening their adaptability to heterogeneous feedstocks, and deepening mechanistic understanding to support more precise process control and valorization oriented toward specific products.

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Abbreviations

The following abbreviations are used in this manuscript:

MAP	Microwave-assisted pyrolysis
FJH	Flash joule heating
SCWG	supercritical water gasification
MSW	Municipal solid waste
ASW	Agricultural solid waste
ISW	Industrial solid waste
HTC	hydrothermal carbonization
AD	Anaerobic digestion
DC	direct current
AC	alternating current
RF	radio frequency
FG	flash graphene

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