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REVIEW

Waste-to-Energy Innovations and Advances in Hydrothermal Carbonization, Microwave, and Pyrolysis Processes: A Review

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ABSTRACT

The accelerating global generation of municipal solid waste, coupled with escalating energy demands, presents one of the most pressing sustainability challenges of the 21st century. Conventional waste disposal pathways, such as landfilling and incineration, exacerbate environmental degradation and resource loss. In response, thermochemical technologies—specifically hydrothermal carbonization (HTC), microwave-assisted processing, and pyrolysis—have emerged as promising strategies for waste valorization and renewable energy recovery. This review critically examines recent advancements in these technologies, emphasizing their roles in converting diverse waste streams into high-value energy carriers and carbon-rich materials. Comparative analysis reveals that HTC operates efficiently under subcritical water conditions, producing hydrochar with tunable physicochemical properties ideal for soil amendment and carbon sequestration. Microwave processing offers rapid, uniform heating with lower energy input and shorter reaction times, enhancing process scalability and efficiency. Pyrolysis, a more established technology, provides high bio-oil and syngas yields suitable for fuel production and chemical synthesis. However, trade-offs in energy balance, process optimization, and emissions management persist. Key findings indicate that hybrid approaches, catalyst innovations, and integration with renewable systems can substantially improve overall energy efficiency and environmental performance. Future research should focus on techno-economic assessments, lifecycle sustainability analyses, and pilot-scale demonstrations to bridge the gap between laboratory success and industrial implementation, advancing the global transition from waste to wealth.

Keywords: Waste-to-energy, Hydrothermal carbonization, Microwave-assisted Pyrolysis, Biochar, Circular economy, Renewable energy

1. Introduction

The twin challenges of waste proliferation and energy scarcity have become central to global sustainability discourse. According to the World Bank's What a Waste 2.0 report, global municipal solid waste (MSW) generation is projected to rise from 2.01 billion tons in 2018 to 3.40 billion tons by

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2050, driven primarily by urbanization, population growth, and industrial expansion [1]. Concurrently, escalating energy demands are expected to increase by nearly 50% by 2050, continuing to place immense pressure on depleting fossil fuel reserves, intensifying concerns over greenhouse gas (GHG) emissions and climate instability [2]. Untreated or mismanaged waste imposes high environmental and economic costs, including leachate generation, methane release from landfills, and soil and groundwater contamination [3]. Economically, the disposal of high-calorific-value biomass and plastic residues represents a loss of recoverable energy and materials, undermining resource efficiency. Moreover, the global waste management sector contributes approximately 5% of total anthropogenic GHG emissions, emphasizing the urgent need for transformative waste-to-energy (WtE) approaches [4–8]. In this context, the transition toward circular and low-carbon energy systems has emerged as an imperative [9]. The circular economy (CE) paradigm promotes resource recovery, valorization, and closed-loop material cycles, thereby minimizing waste generation and dependence on non-renewable energy [10, 11]. Within this framework, waste is no longer viewed as a liability but as a renewable feedstock for energy and material generation [12]. Thermochemical conversion pathways, capable of producing fuels, syngas, and carbonaceous materials from heterogeneous waste streams, play a pivotal role in advancing this transition. Thermochemical conversion technologies comprising hydrothermal carbonization (HTC), microwave-assisted processing, and pyrolysis offer distinct advantages over biochemical routes such as anaerobic digestion or composting [13]. Biochemical methods, though suitable for specific organic fractions, are limited by slow kinetics, sensitivity to moisture, and low energy yields [14, 15]. In contrast, thermochemical processes operate under elevated temperatures and controlled atmospheres, decomposing a broad spectrum of organic waste (including wet, plastic-rich, and lignocellulose feedstocks) into high-energy products such as hydro char, bio-oil, and syngas [16–19]. Hydrothermal Carbonization (HTC) occurs under subcritical water conditions (180–250 °C, 2–4 MPa), converting wet biomass into hydro char without the need for energy-intensive drying [20]. The resulting hydro char exhibits high carbon content, tunable surface functionality, and potential applications in energy storage, soil amendment, and carbon sequestration [21]. Microwave Processing employs electromagnetic radiation to achieve rapid, uniform heating at the molecular level [22]. Compared to conventional heating, it enhances reaction efficiency, reduces energy consumption, and improves product uniformity. Microwave-assisted pyrolysis and hydrothermal systems have demonstrated improved yields of bio-oil and char with lower process times [23]. Pyrolysis, a more established technology, thermally decomposes dry biomass at 300–700 °C in the absence of oxygen, yielding bio-oil, biochar, and syngas. Its process flexibility allows for tuning of product ratios depending on target applications fuel synthesis, activated carbon production, or gasification feedstock [24–26]. Collectively, these processes embody the "waste-to-wealth" paradigm, turning environmental burdens into valuable energy carriers and carbon-rich products [27]. The integration of thermochemical routes with renewable energy systems such as solar-assisted pyrolysis or hybrid HTC gasification schemes offers additional potential for improving overall system sustainability and energy recovery [28, 29]. Recent technological milestones underscore this progress. Innovations in catalyst design, such as transition metal oxides and carbon-based catalysts, have enhanced conversion efficiency and selectivity [30]. Hybrid systems combining microwave and HTC or pyrolysis and gasification are being developed for improved energy yields and waste versatility [15]. Furthermore, life cycle assessments (LCA) and techno-economic analyses (TEA) are increasingly used to benchmark sustainability and cost-effectiveness at industrial scales [31]. Despite significant advancements, several knowledge and implementation gaps persist in the thermochemical valorization of waste [32]. Most existing reviews focus narrowly on single processes (e.g., only pyrolysis or HTC) or specific feedstocks, neglecting comparative performance analysis and hybrid integration frameworks [33]. Moreover, limited attention has been given to process scalability, reactor engineering, and supply chain integration factors crucial for industrial deployment [34]. Another critical gap lies in the integration of process data across thermal, environmental, and economic dimensions [35]. There remains insufficient understanding of the synergistic potential between these technologies, such as coupling HTC with pyrolysis to sequentially utilize wet and dry waste fractions or using microwave pre-treatment to enhance char reactivity [36]. Furthermore, policy and regulatory frameworks for large-scale thermochemical waste management remain underdeveloped in many regions, hindering commercialization [37]. Comparatively assess the three emerging thermochemical technologies, HTC, microwave processing, and pyrolysis, focusing on conversion mechanisms, product distribution, and energy efficiency [38]. Evaluate

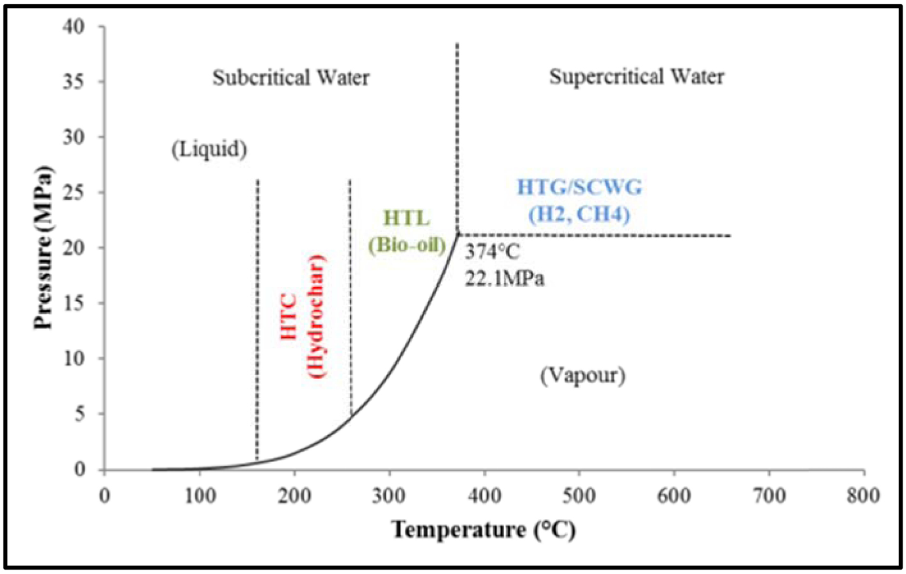

Fig. 1. Hydrothermal processes parameters [20].

their integration potential within sustainable and circular energy systems, including hybrid and cascading configurations. Identify research priorities and future directions, encompassing catalyst innovations, process optimization, carbon footprint reduction, and policy alignment for industrial-scale deployment [39]. By synthesizing recent research and highlighting cross-technology synergies, this work contributes to establishing a systematic roadmap for advancing thermochemical waste valorization from laboratory success to commercial-scale sustainability, reinforcing its central role in global waste-to-energy transitions [40]. [20] has been reported that the product state of the hydrothermal process can be solid, liquid, or gaseous, depending on the operating conditions (temperature and pressure). Hydrothermal carbonization (HTC) occurs between 150 and 250 ˚C, with pressures ranging from 0.5 to 4 MPa; hydrothermal liquefaction (HTL) occurs between 150 and 350 ˚C, with pressures ranging from 3 to 6 MPa; and hydrothermal gasification (HTG) occurs above 350 ˚C, with pressures exceeding 8 MPa, as detailed in Fig. 1.

2. Feedstock overview and characterization

2.1. Types of waste feedstocks

Thermochemical conversion technologies rely heavily on the nature and composition of waste feedstocks, which determine process efficiency, product distribution, and energy recovery potential. Waste suitable for hydrothermal carbonization (HTC), microwave-assisted processing, and pyrolysis can be broadly categorized into six major classes: lignocellulose biomass, municipal solid waste (MSW), oily sludge, agricultural residues, food waste, and sewage sludge [41]. Lignocellulose biomass includes forestry residues, wood chips, and crop stalks, composed primarily of cellulose (35–50%), hemicellulose (20–35%), and lignin (10–30%) [42]. Its high volatile content and low ash fraction make it ideal for pyrolysis and microwave-assisted processing, producing high-quality bio-oil and Biochar. Municipal solid waste (MSW) represents a heterogeneous mixture of paper, plastics, textiles, and organic matter. Its complex composition necessitates sorting and pre-treatment to ensure consistent feedstock quality. However, MSW remains a globally abundant and underutilized resource, exceeding 2 billion tons annually, with significant potential for waste-to-energy applications [43]. Oily sludge, generated from petroleum refining and wastewater treatment, contains hydrocarbons, water, and solids. Thermochemical processing of oily sludge can recover valuable oils while reducing hazardous waste volumes [44, 45]. Agricultural residues such as rice husks, wheat straw, and corn stover are widely available and renewable. Seasonal variations in availability influence supply chain stability, but their high carbon and low nitrogen content make them suitable for biochar production through pyrolysis [46, 47]. Food waste, rich in moisture (60–80%), proteins, and lipids, is better suited for HTC, which can process wet feedstocks without prior drying. It is an excellent precursor for hydrochar used in soil enhancement and adsorption applications [41].

Sewage sludge, produced in large quantities during wastewater treatment, contains organic matter, heavy metals, and nutrients. Its high moisture and ash content make HTC and microwave-assisted hydrothermal processing the preferred routes, improving dewaterability and energy recovery while reducing environmental risks [48]. Global availability of these feedstocks varies by geography and season. Agricultural residues dominate in Asia and sub-Saharan Africa, while MSW and sewage sludge are more concentrated in urbanized regions of Europe and North America. The seasonal variability of crop residues can affect feedstock supply chains, necessitating integrated collection, storage, and blending strategies to ensure consistent feedstock input for continuous thermochemical operations.

2.2. Physicochemical properties

The physicochemical properties of feedstocks, particularly those derived from proximate and ultimate analyses, critically influence their suitability for different thermochemical pathways. Proximate analysis determines moisture, volatile matter, ash, and fixed carbon content, indicating the degree of combustibility and char yield. Ultimate analysis measures elemental composition carbon (C), hydrogen (H), oxygen (O), nitrogen (N), and sulfur (S) from which fuel quality and emission potential can be inferred. Higher heating value (HHV) or calorific value quantifies energy density, typically ranging from 10-25 MJ/kg depending on feedstock type [49]. Feedstocks with high moisture content (e.g., food waste, sewage sludge) are less suitable for dry thermochemical processes such as pyrolysis but perform well under hydrothermal conditions, where water acts as both reactant and medium. Conversely, low-moisture materials like lignocellulose biomass and plastics exhibit higher energy yields in microwave or conventional pyrolysis [50]. The ash composition notably the content of alkali and alkaline earth metals (K, Na, Ca, Mg) affects catalytic behavior, melting point, and fouling tendencies during conversion. High ash content can lead to slagging and sintering, reducing process efficiency [51]. However, controlled mineral content can promote secondary reactions, influencing char porosity and gas evolution.

2.3. Suitability for thermochemical conversion

The suitability of feedstocks for different thermochemical technologies is determined by their chemical composition, moisture level, and ash content. Hydrothermal Carbonization (HTC): Ideal for wet feedstocks (e.g., food waste, sewage sludge) because it operates in water-rich environments. Feedstocks rich in carbohydrates and proteins favor hydro char formation with high oxygen functionality, suitable for soil amendment and adsorption[52]. Microwave-Assisted Processing: Performs optimally with low-to-moderate moisture feedstocks. Materials with high dielectric constants—such as plastics, wood, and oily sludge absorb microwave energy effectively, resulting in rapid heating and enhanced conversion efficiency [53]. Pyrolysis: Requires dry and low-ash feedstocks, such as lignocellulose biomass and agricultural residues, to produce bio-oil and char with high energy density. Moisture removal and particle size reduction are essential pretreatment steps. Co-processing and blending of feedstocks offer a practical solution for optimizing process performance. For instance, blending wet sewage sludge with dry agricultural residues can balance moisture and improve char yield. Similarly, co-pyrolysis of plastics with biomass enhances hydrogen production and reduces tar formation [54]. Effective pretreatment such as drying, shredding, de-ashing, or catalytic impregnation improves feedstock homogeneity and reactor stability. Advanced characterization methods (FTIR, TGA, SEM-EDS) further enable understanding of reaction pathways and kinetics, facilitating process optimization [55].

3. Hydrothermal carbonization (HTC)

3.1. Reaction mechanism and process conditions

Hydrothermal carbonization (HTC) involves the conversion of wet biomass into carbon-rich hydro char under subcritical water conditions (typically 180–250 °C, 2–6 MPa pressure) [56]. The process mimics natural coal formation but occurs in hours rather than millennia [57, 58].

Key reaction parameters include:

1- Temperature: Governs the degree of carbonization. Higher temperatures (>230 °C) favor decarboxylation and aromatization, reducing oxygen content.
2- Pressure: Autogenously pressure maintains water in liquid form, enhancing hydrolysis reactions.
3- Residence time: Usually 1–12 h. Longer times promote carbon densification but may reduce yield.
4- Water-to-solid ratio: Typically, 5–10:1, influencing heat transfer and mass diffusion.

Main reaction pathways:

Table 1. Applications of hydrochar exhibits multi functionality due physiochemical properties.

Application	Description	References
Soil Amendment	Improves soil carbon content, nutrient retention, and microbial activity	[61]
Activated Carbon	Precursor for porous carbon via chemical activation (KOH, $ZnCl_2$)	[62]
Energy Storage	Used in super capacitors due to high surface area and conductivity	[63]
Carbon Sequestration	Long-term stable carbon sink with potential for CO_2 reduction	[64]

A- Dehydration: Removal of –OH groups forming C=C bonds.
B- Decarboxylation: Loss of CO_2, reducing O/C ratio.
C- Polymerization and condensation: Formation of aromatic networks yielding hydro char.

3.2. Product formation and characterization

Hydro char is the solid product obtained after HTC. Its yield typically ranges between 40–70 wt.%, depending on feedstock composition (carbohydrates, lignin, lipids) and process temperature.

Key properties:

1- Higher Heating Value (HHV): 20–30 MJ/kg, approaching sub-bituminous coal.
2- Surface area: 10–300 m^2/g, tunable by activation or post-treatment.
3- Functional groups: Hydro char contains hydroxyl, carboxyl, and carbonyl moieties, enabling adsorption and catalytic applications. Liquid by-products include organic acids (mainly acetic acid), furfurals, and phenolic compounds; gaseous products (CO_2, CH_4, minor CO, H_2) arise from decarboxylation and reforming reactions [59, 60].

The hydrothermal carbonization (HTC) process presents several technical and operational challenges alongside emerging opportunities for optimization and innovation [65]. One of the primary challenges lies in the scale-up of continuous-flow HTC reactors, which demand precise control of temperature and pressure to ensure consistent product quality and process efficiency [66, 67]. Another critical issue is reactor corrosion, often resulting from the presence of organic acids, salts, and other corrosive intermediates formed under high-pressure and subcritical water conditions [68]. Additionally, maintaining a favorable energy balance remains a concern, as the high thermal energy requirements for heating and pressurizing the system can offset the net carbon gains if the process is not adequately optimized [69]. Despite these challenges, significant opportunities exist to enhance the sustainability and versatility of HTC. Integration with wastewater treatment systems offers a dual benefit of nutrient recovery and sludge valorization, transforming waste streams into valuable carbon materials [70]. Moreover, co-hydrothermal carbonization (co-HTC) of mixed feedstocks, such as sewage sludge combined with lignocellulose residues, has shown promise in improving carbon yield and hydro char quality [71].

4. Microwave-assisted thermochemical processing

4.1. Principles of microwave heating

Microwave-assisted thermochemical processing harnesses electromagnetic radiation, typically at 2.45 GHz—to heat materials through dipole rotation and ionic conduction mechanisms. In polar molecules such as water and certain organic compounds, alternating electromagnetic fields cause molecular dipoles to oscillate rapidly, generating heat via molecular friction [72]. In parallel, ionic conduction arises when free ions in the material move in response to the electric field, converting electrical energy into heat through resistance losses [73]. These phenomena are governed by the dielectric properties of the feedstock, which determine its ability to absorb and convert microwave energy into heat [74]. Unlike conventional heating, which transfers heat from the surface inward, microwave irradiation enables selective volumetric heating, leading to enhanced thermal uniformity and process efficiency [75]. This selective heating behavior is particularly advantageous in biomass processing, where heterogeneous compositions and moisture contents often cause uneven temperature gradients during conventional pyrolysis. As a result, microwave heating offers improved control over reaction kinetics, product distribution, and carbonization efficiency [76].

4.2. Reactor design and operating parameters

The efficiency of microwave-assisted processing depends critically on reactor design and operating parameters such as frequency, power density, and heating rate. Standard microwave reactors operate at 2.45 GHz with adjustable power levels ranging from 300 to 3000 W, enabling rapid heating rates

Table 2. Comparison between conventional and microwave-assisted pyrolysis.

Parameter	Conventional Pyrolysis	Microwave-Assisted Pyrolysis	Reference
Heating mechanism	Conductive/convective	Dipole rotation & ionic conduction	[88]
Heating rate	5–50 °C/min	100–300 °C/min	[89]
Energy efficiency	Moderate	High	[90]
Bio-oil quality	Oxygenated	Lower oxygen, higher hydrocarbons	[91]
Equipment cost	Low–moderate	High	[92]
Scale-up potential	Mature	Developing	[93]

often exceeding 100 °C/min [77]. The power density directly affects the heating uniformity and reaction intensity, influencing the yield and composition of bio-oil, syngas, and biochar. Reactor geometry and cavity design are optimized to minimize reflection losses and ensure even field distribution. Recent advances include the use of catalyst-assisted microwave pyrolysis, where catalysts such as zeolites, Ni/Al_2O_3, or biochar-supported metals enhance reaction selectivity, reduce activation energy, and promote deoxygenation reactions [78]. Hybrid configurations that combine microwave heating with conventional conduction or fluidized-bed systems have also been explored to overcome limitations in penetration depth and scale-up [79]. The overall system design must balance electromagnetic field distribution, thermal management, and feedstock throughput for consistent and energy-efficient operation [80].

4.3. Product distribution and quality

The distribution and quality of products obtained from microwave-assisted pyrolysis, namely bio-oil, syngas, and biochar, depend strongly on feedstock composition and operational settings [81]. High microwave power and rapid heating favor secondary cracking reactions, resulting in greater syngas yields and reduced bio-oil fractions, while lower temperatures ($\leq$500 °C) typically favor bio-oil formation [82]. Biomass with high lignin content tends to produce more aromatic compounds and carbon-rich chars, whereas carbohydrate-rich feedstocks yield oxygenated volatiles and lighter hydrocarbons. The inclusion of catalysts during microwave pyrolysis enhances bio-oil quality by reducing oxygenated compounds and increasing hydrocarbon selectivity [83]. The resulting biochar exhibits high surface area, micro-porosity, and functional groups suitable for adsorption, energy storage, and soil remediation [84]. Importantly, the unique heating mechanism of microwaves allows for fine-tuning of the product profile by adjusting residence time, power density, and feedstock particle size [85].

4.4. Advantages and challenges

Microwave-assisted thermochemical processing offers several distinct advantages over conventional pyrolysis, including enhanced energy efficiency, rapid reaction times, and uniform heating profiles [76]. The direct conversion of electromagnetic energy into thermal energy reduces heat losses, while volumetric heating ensures a more homogeneous temperature distribution, improving reaction control and yield. Additionally, microwave systems can be started and stopped quickly, providing operational flexibility and shorter cycle times. However, significant challenges remain. The equipment cost of microwave reactors is relatively high due to specialized materials and waveguide design [86]. Moreover, the limited penetration depth of microwaves (typically 1–5 cm in most biomass types) restricts scalability and uniform heating in large reactors [79]. Research efforts are ongoing to overcome these limitations through the development of microwave subsectors, improved reactor geometries, and hybrid systems combining microwaves with auxiliary heating methods [87]. Addressing these challenges is essential for the commercial viability and large-scale deployment of microwave-assisted bioenergy technologies [86]. As shown in Table 2.

5. Conventional and advanced pyrolysis

5.1. Types of pyrolysis processes

Pyrolysis is a thermochemical decomposition process that converts organic materials into bio-oil, biochar, and syngas under an oxygen-deficient atmosphere. Depending on heating rate, temperature, and residence time, pyrolysis can be classified into slow, fast, catalytic, and co-pyrolysis processes. Slow pyrolysis, performed at moderate temperatures (350–500 °C) and long residence times (hours), maximizes biochar yield [94]. In contrast, fast pyrolysis, typically conducted at 450–600 °C with rapid heating rates (>100 °C/s) and short vapor residence times

(<2 s), favors bio-oil production [95]. Catalytic pyrolysis employs catalysts such as zeolites, metal oxides, or activated carbon to enhance deoxygenation and aromatic hydrocarbon formation, improving the quality of bio-oil [96, 97]. Co-pyrolysis, involving the simultaneous conversion of biomass with materials like plastics or oily sludge, leverages synergistic effects that enhance hydrogen transfer and overall carbon recovery [98]. Common reactor configurations include fixed-bed, fluidized-bed, and auger reactors, each offering different heat transfer and scalability characteristics [99]. Fluidized-bed systems are particularly favored for industrial-scale operations due to superior heat distribution and continuous operation capabilities.

5.2. Process optimization

Optimizing pyrolysis involves fine-tuning temperature, heating rate, residence time, and catalyst selection to achieve targeted yields of bio-oil, biochar, and syngas. The temperature plays a dominant role: low temperatures (350–450 ˚C) favor char formation, while high temperatures (600–700 ˚C) enhance gaseous product yields [100]. The heating rate influences the volatilization and secondary cracking of vapors, with fast heating promoting higher liquid yields. Catalysts such as HZSM-5, Ni-based, and CaO are often employed to enhance deoxygenation reactions, reduce acidity, and increase the aromatic content of bio-oil [101]. Additionally, co-processing biomass with plastic waste or oily sludge has gained attention for improving hydrogen availability and thermal efficiency, resulting in upgraded oil with lower oxygen content [102]. These hybrid feedstock systems also enhance process sustainability by recycling problematic waste streams into valuable fuels and materials. Advanced kinetic modeling and computational fluid dynamics (CFD) are increasingly applied for reactor and parameter optimization, allowing predictive control over product distribution and process energy balance [103].

5.3. Product characterization

The products of pyrolysis bio-oil, biochar, and syngas exhibit diverse physicochemical characteristics depending on feedstock type and process conditions. Bio-oil typically contains phenolic, aliphatic, ketonic, and acidic compounds, derived from the depolymerization of lignin, cellulose, and hemicellulose [104]. Catalytic pyrolysis reduces oxygenated compounds, yielding a more stable, energy-dense liquid with heating values up to 35 MJ/kg. The properties of biochar, such as surface area, porosity, and functional groups, are influenced by the pyrolysis temperature and heating rate. Higher temperatures increase aromaticity and surface area, improving its applicability in soil remediation, adsorption, and energy storage [105]. Meanwhile, syngas, mainly composed of CO, H_2, CO_2, and CH_4, serves as a valuable feedstock for combustion, Fischer-Tropsch synthesis, or hydrogen production [106]. Optimizing pyrolysis conditions can balance these product streams for specific applications, contributing to circular carbon economy strategies.

5.4. Integration with other technologies

Integrating pyrolysis with other thermochemical and hydrothermal processes enhances energy efficiency, carbon recovery, and product flexibility. Pyrolysis–gasification hybrid systems combine the carbonization and reforming steps, allowing simultaneous production of syngas and upgraded biochar while reducing tar formation [15]. Similarly, HTC-pyrolysis hybrid configurations utilize hydro char as an intermediate feedstock for secondary pyrolysis, improving overall carbon yield and energy density [107]. These integrated systems enable more complete utilization of biomass and waste materials, minimizing emissions and enhancing process circularity. Coupling with renewable energy sources such as solar or microwave-assisted heating further reduces fossil-based energy input and carbon footprint [108]. Future developments in process intensification, reactor design, and energy integration will be key to achieving scalable, sustainable pyrolysis-based biorefinery capable of producing renewable fuels and carbon materials for diverse industrial applications [109]. The Fig. 2 (a & b) shown the Schematic flow of pyrolysis and product recovery [110].

6. Comparative evaluation of thermochemical routes

6.1. Process efficiency and energy recovery

The efficiency and energy recovery potential of thermochemical routes such as hydrothermal carbonization (HTC), microwave-assisted pyrolysis, and conventional pyrolysis vary significantly depending on feedstock composition and process parameters. HTC is particularly effective for wet biomass, offering energy recoveries of 70–85% due to its minimal drying requirements and high hydrochar yield [111]. However, its energy densification ratio is lower than that of pyrolysis-derived biochar due to the formation of oxygenated intermediates. In contrast,

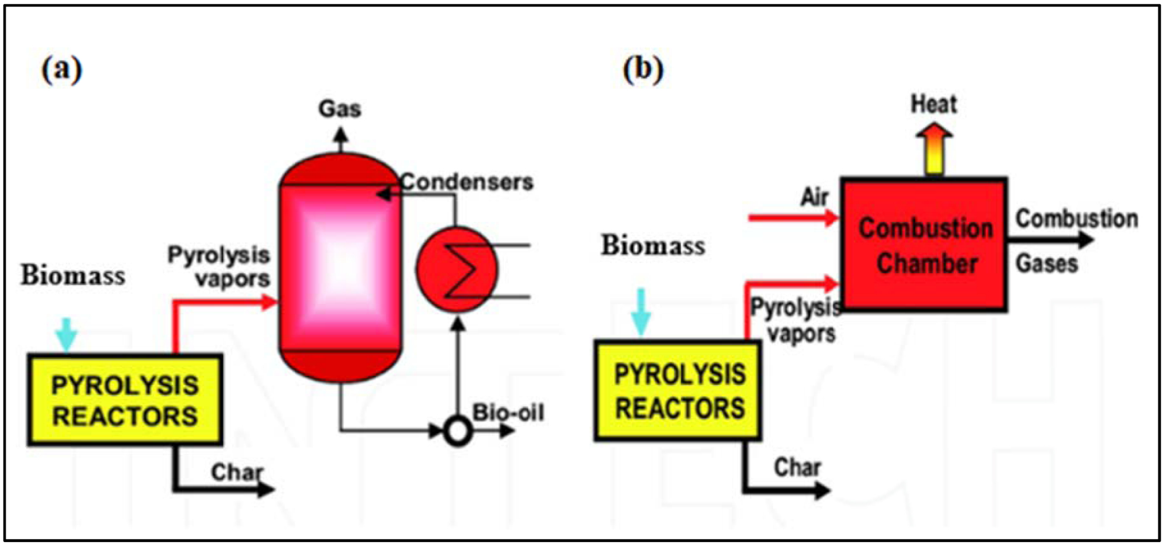

Fig. 2. Schematic flow of pyrolysis and product recovery (a) biochar and biooil production, (b) biochar and heat production [110].

microwave-assisted pyrolysis demonstrates superior energy conversion efficiency (up to 80–90%) and reduced reaction times, facilitated by rapid and uniform heating mechanisms [112]. Conventional fast pyrolysis offers high liquid fuel yield (55–70%) but requires external heating, leading to higher energy input and heat losses [113]. When comparing emission profiles, HTC generates lower gaseous emissions but higher aqueous effluents rich in organics, whereas pyrolysis and microwave systems emit CO_2 and light hydrocarbons depending on the feedstock's C/H ratio. Recent studies suggest that hybrid configurations, such as microwave-assisted catalytic pyrolysis, can optimize both energy recovery and emission performance, making them suitable for scalable biorefinery applications [114].

6.2. Environmental performance

From an environmental perspective, thermochemical conversion technologies exhibit contrasting impacts in terms of greenhouse gas (GHG) emissions, carbon sequestration, and resource recovery potential. HTC stands out for its potential in carbon sequestration, as hydrochar produced under wet conditions retains a large portion of biogenic carbon in a chemically stable form, enabling long-term soil carbon storage [6, 25, 115–117]. Conversely, pyrolysis-derived biochar also provides significant sequestration potential, with carbon stability exceeding 70% and the added benefit of improving soil fertility when applied as a soil amendment [118]. Microwave-assisted processes generally exhibit lower GHG emissions than conventional pyrolysis due to shorter residence times, lower energy consumption, and reduced heat losses [119]. Life-cycle assessment (LCA) studies show that integrating HTC or pyrolysis with waste management systems can result in net-negative carbon emissions, especially when coupled with carbon capture or renewable power sources [120]. Nevertheless, the environmental footprint depends heavily on feedstock logistics, process scale, and by-product valorization strategies [121].

6.3. Economic feasibility

The economic viability of HTC, microwave-assisted, and conventional pyrolysis depends on capital expenditure (CAPEX), operational expenditure (OPEX), and local market conditions. Conventional pyrolysis is currently the most commercially mature route, with moderate CAPEX and scalable reactor technologies, but its OPEX remains high due to feedstock drying and energy-intensive heating [122]. HTC offers lower OPEX for wet feedstocks since it eliminates pre-drying costs, though the requirement for high-pressure reactors increases initial capital investment [123]. Microwave-assisted systems are still primarily at the pilot scale, constrained by high equipment and maintenance costs associated with microwave generators and limited penetration depth, which affects scalability [124]. Economic sensitivity analyses indicate that profitability depends strongly on biochar and bio-oil market prices, energy tariffs, and feedstock cost variations [125]. Integration of thermochemical systems with waste valorization and renewable energy inputs can significantly enhance economic performance and return on investment,

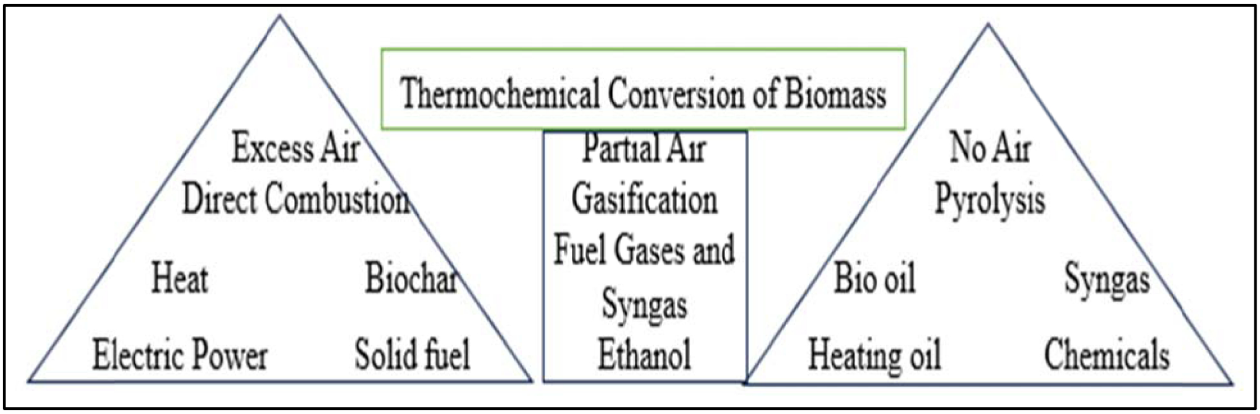

Fig. 3. Product utilization map for a circular bioenergy system [127].

particularly in regions with biomass surpluses or favorable policy incentives [126].

7. Product valorization and utilization pathways

The thermochemical conversion of biomass yields a diverse range of solid, liquid, and gaseous products, each possessing distinct physicochemical characteristics and utilization potentials that contribute to the development of a circular bioeconomy (see Fig. 3) [127].

7.1. Solid products (Hydrochar, Biochar)

The solid fraction, comprising hydrochar from hydrothermal carbonization and biochar from pyrolysis, exhibits high carbon content, porous structure, and abundant surface functionalities, making it suitable for applications as adsorbents, soil conditioners, and electrode materials. As adsorbents, biochar demonstrates high affinity for heavy metals and organic pollutants due to its oxygenated surface groups and large specific surface area [128, 129]. When applied as a soil amendment, biochar enhances nutrient retention, microbial activity, and carbon sequestration potential, contributing to long-term soil fertility and greenhouse gas mitigation [19]. Furthermore, its high electrical conductivity and stability enable its use in energy storage devices such as super capacitors and lithium-ion batteries [130].

7.2. Liquid products (Bio-oil, Aqueous phase)

The liquid fraction, primarily bio-oil and aqueous condensates, serves as a valuable source of renewable chemicals and fuels. However, the high oxygen content, acidity, and instability of crude bio-oil necessitate upgrading via catalytic hydro treatment, esterification, or emulsification processes to produce transportation-grade fuels [131]. Integrating bio-oil refining with existing petrochemical infrastructures allows for co-processing in fluid catalytic cracking (FCC) units, thus facilitating the transition toward low-carbon refineries [132, 133]. The aqueous phase, rich in organic acids and sugars, can be valorized through microbial fermentation or reforming to generate value-added biochemical and hydrogen [134].

7.3. Gaseous products (Syngas, Hydrogen)

The gaseous products, composed mainly of CO, H_2, CH_4, and CO_2, can be utilized directly for combined heat and power (CHP) generation or upgraded for use in fuel cells [135, 136]. Syngas rich in hydrogen has significant potential for clean fuel applications, particularly when optimized through steam reforming or catalytic conditioning. Coupling syngas utilization with solid oxide or proton exchange membrane (PEM) fuel cells can enhance overall energy efficiency while reducing carbon emissions. Moreover, integrating gasification-derived hydrogen with carbon capture and utilization (CCU) technologies presents a promising route toward negative-emission energy systems [137–139]. Collectively, the integrated valorization of solid, liquid, and gaseous products forms the foundation of a sustainable circular bioenergy system. Such an approach not only maximizes resource efficiency but also mitigates environmental impacts, contributing to the realization of carbon-neutral or carbon-negative pathways [140].

8. Emerging trends and future research directions

Rapid advancements in biomass conversion science and process engineering are paving the way for next-generation thermochemical technologies that prioritize efficiency, digitalization, and sustainability. The integration of novel hybrid systems, artificial intelligence, and policy aligned sustainability frameworks marks a transformative phase toward circular and carbon-neutral bioenergy production [141].

8.1. Hybrid and cascade systems

Emerging hybrid thermochemical configurations such as hydrothermal carbonization (HTC) coupled with pyrolysis or gasification, and microwave-assisted HTC represent promising pathways for maximizing carbon recovery and overall energy yield [107]. These cascade systems enable sequential valorization of biomass components, where the hydrochar from HTC can serve as a precursor for secondary pyrolysis to produce bio-oil or syngas, thus enhancing process integration and product flexibility [142]. The use of microwave irradiation further accelerates reaction kinetics, reduces activation energy barriers, and enables rapid, selective heating, improving both yield and energy efficiency [23]. Future research should focus on optimizing these coupled systems through process intensification, reactor-scale modeling, and in-situ monitoring to bridge the gap between laboratory-scale demonstrations and industrial deployment.

8.2. Artificial intelligence and process optimization

The digital transformation of bioenergy systems is being accelerated by the integration of artificial intelligence (AI), machine learning (ML), and digital twin technologies for process modeling, predictive control, and optimization [143, 144]. Data-driven algorithms can identify non-linear correlations among key operating parameters such as temperature, pressure, and residence time enabling real-time optimization of conversion efficiency and emissions reduction [145, 146]. Digital twins, as dynamic virtual replicas of reactors, facilitate scenario testing, fault detection, and life-cycle analysis without physical downtime. These intelligent systems will become essential for transitioning from empirical experimentation toward adaptive, self-optimizing biomass conversion platforms [147]. Integrating AI models with sensor-based feedback loops and process automation offers a powerful approach to scaling up HTC and pyrolysis technologies under Industry 4.0 frameworks.

8.3. Sustainability and policy integration

Achieving large-scale deployment of bio-based energy systems requires alignment with sustainability policies and climate-neutral strategies. Current research emphasizes the importance of integrating bioenergy development with the United Nations Sustainable Development Goals (UN SDGs), particularly SDG 7 (Affordable and Clean Energy), SDG 12 (Responsible Consumption and Production), and SDG 13 (Climate Action) [148]. Regional circular economy initiatives, including carbon pricing, biochar credits, and renewable energy mandates, provide enabling frameworks for industrial adoption. Life cycle assessment (LCA) and techno-economic analysis (TEA) are critical tools for quantifying environmental benefits and ensuring policy compliance [149, 150]. Future research must focus on integrating environmental modeling with socio-economic metrics to ensure that emerging bioenergy technologies not only achieve carbon neutrality but also promote equitable resource utilization and climate resilience across regions.

This review has comprehensively examined the advancements, performance characteristics, and sustainability implications of hydrothermal carbonization (HTC), microwave-assisted processing, and pyrolysis as thermochemical pathways for transforming waste into high-value energy carriers [151]. Collectively, these technologies demonstrate exceptional potential to convert diverse organic residues into biochar, bio-oil, and syngas, thereby enhancing both energy yield and resource efficiency [152]. Comparative analyses reveal that HTC offers superior handling of wet biomass with minimal drying requirements, pyrolysis achieves high carbon recovery and biochar stability, and microwave-assisted processes enable rapid, uniform heating that improves conversion kinetics and product quality. Together, these innovations contribute to reduced greenhouse gas emissions, enhanced carbon sequestration, and circular economy integration, underlining their environmental and economic advantages over conventional waste disposal or fossil-based energy systems [20]. The decarboxylation and dehydration processes they are main reactions occurred in the thermochemical conversion processes [32].

9. Conclusion

A key insight from this synthesis is the importance of process integration and hybridization. Coupling HTC with pyrolysis or microwave treatment enables cascade energy recovery and sequential valorization of carbon-rich intermediates, thereby improving system efficiency and lifecycle performance. Advances in catalytic upgrading, real-time process monitoring, and digital optimization through machine learning and artificial intelligence are accelerating the transition toward adaptive and high-yield thermochemical systems. Moreover, techno-economic and life cycle assessments consistently affirm the carbon mitigation potential of these technologies, provided that energy inputs, feedstock logistics, and scaling constraints are optimized. Moving forward, a roadmap for scaling thermochemical conversion in developing regions should prioritize modular, low-cost reactor designs utilizing locally available biomass feedstocks. Integration with decentralized power grids and municipal waste management systems can promote energy independence and reduce landfill pressure, while generating economic value through carbon credits and bio-based product markets. Such systems, when coupled with policy incentives and capacity-building initiatives, can catalyze sustainable industrialization and environmental resilience. The integration of waste-to-energy systems into sustainable urban and industrial ecosystems offers transformative opportunities for achieving resource circularity and low-carbon development. Synergies between HTC, pyrolysis, and microwave systems can be harnessed within eco-industrial parks, where process residues and heat streams are internally recycled. Embedding these systems within broader sustainability frameworks such as the UN Sustainable Development Goals (SDGs) and national decarbonization agendas will further strengthen their societal and policy relevance. Looking toward 2030–2050, thermochemical conversion technologies are poised to play a critical role in global net-zero energy transitions. By coupling waste valorization with carbon capture, hydrogen production, and biochar-based carbon storage, future energy systems can move beyond neutrality toward net-negative emissions. Continued research should emphasize process intensification, multi-scale modeling, and integration with renewable electricity sources to realize fully closed-loop, carbon-smart energy ecosystems. In essence, turning “waste to wealth” through advanced thermochemical platforms will not only redefine waste management but also underpin the foundation of a sustainable, circular, and climate-resilient energy future.

The limitations and future perspectives despite significant progress in hydrothermal carbonization, microwave-assisted processing, and pyrolysis, several limitations still constrain their large-scale deployment for sustainable energy production. The constraints and future views despite major advances in hydrothermal carbonization, microwave-assisted processing, and pyrolysis, certain restrictions continue to prevent their widespread use for sustainable energy production. Current studies are predominantly limited to laboratory or pilot scales, where process parameters are optimized under controlled conditions that may not accurately reflect the heterogeneity of real biomass feedstocks or the variability of industrial environments. Challenges such as reactor scalability, feedstock pre-treatment, energy input optimization, and the high cost of catalysts and microwave systems hinder economic feasibility. Moreover, the lack of standardized life cycle assessment frameworks and insufficient integration with renewable power grids impede the holistic evaluation of environmental benefits. Future research should focus on developing integrated, hybrid thermochemical platforms that combine the advantages of HTC, microwave, and pyrolysis processes while leveraging artificial intelligence, digital twins, and advanced modeling for process control and predictive optimization. Cross-disciplinary efforts linking materials science, process engineering, and sustainability policy are crucial to bridge the gap between laboratory innovation and industrial implementation. Ultimately, achieving full-scale circular waste-to-energy systems will depend on techno-economic optimization, carbon-neutral design, and policy-driven incentives that align these technologies with the global transition toward net-zero energy systems by 2050.

Conflict of interest

The author declares no conflict interest.

Ethical approval

Not applicable.

Data availability

The data will be available upon request.

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Author contributions

Ali Mohammed Saleh: formal analysis, validation, writing-original, Noah Mohammed Saleh: data curation, writing-original, Mahmod A. Abdulqader: conceptualization, methodology, writing review and editing, Hadi Hamdi Mahdi: data curation, conceptualization, Jafar Keighobadi: research administration methodology, writing-review and editing, Omar K. Ahmed: supervision, research administration, Khalil Farhan Yassin: writing-review and editing, Azil Bahari bin Alias: research administration methodology, Omar abed Habeeb: writing and editing, Ibrahim Awad Mohammed: writing and editing.

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