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Enhancing wastewater treatment with engineered biochar from microwave-assisted approach - A comprehensive review

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Abstract

The growing global concern over water pollution has urgently demanded cost-effective and highly efficient methods and materials for removing pollutants. Biochar is a promising material for use as an adsorbent due to its abundance, low cost, porous surface, and alterable surface functional group. This review provides a detailed insight into the current state-of-art of biochar production from microwave-assisted pyrolysis, activation approaches to improve the physicochemical properties of biochar, and the applications of biochar in various pollutants from wastewater, including heavy metals, dyes, antibiotics and nutrients from aquaculture. Pyrolysis is a promising method for producing biochar, but the drawbacks of conventional pyrolysis are slow processing and low energy efficiency. Microwave-assisted pyrolysis has undergone extensive study due to its distinctive heating mechanism, which facilitates rapid feedstock heating, thereby enhancing energy efficiency and yielding pyrolytic products of improved quality and quantity. The biochar produced has a high surface area (up to 1500 m^2/g) and exhibits different functional groups that are effective for pollutant adsorption from wastewater. Methods for activating biochar based on physical activation with assistance from microwave heating can offer a cost-effective and straightforward approach to producing engineered biochar for large-scale wastewater treatment. Conversely, chemical activation can provide specific surface functional groups tailored to meet requirements for removing pollutants. However, further research is necessary to optimize the production of engineered biochar, enhance its adsorption properties, and develop efficient regeneration techniques for its widespread application in large-scale wastewater treatment systems.

Keywords: Advanced microwave pyrolysis; Activated biochar; Water pollution; Industrial wastewater; Aquaculture wastewater

1. Introduction

Environmental pollution is a pervasive global issue affecting human health, ecosystems, and the climate. The growth of the global population, rapid industrialization, and urbanization have significantly amplified its impact over the past century. Water pollution is a significant consequence of environmental pollution, posing severe threats to aquatic ecosystems, human health, and the sustainability of our planet's water resources. It is forecasted that up to 5.5 billion people will be exposed to polluted water worldwide by 2100 Jones et al. [1]. The pollution sources include industrial wastewater, hospital effluents, runoff from agriculture, livestock, aquaculture, landfill leachates, and domestic discharge [2]. Various technologies have been developed for wastewater treatment, including chemical precipitation, coagulation-flocculation, membrane filtration, ion exchange, reverse osmosis, electrochemical treatment, and adsorption [3-5]. However, conventional technologies have several drawbacks, such as inefficient removal of pollutants at low concentrations, ineffective degradation of pollutants into less toxic or biodegradable byproducts, high operational and maintenance costs, and low energy efficiency [3]. Addressing water pollution necessitates urgently developing and implementing efficient and economically viable treatment solutions that balance environmental sustainability and cost-effectiveness, enabling large-scale adoption and impact.

Biochar, seemingly a cost-effective and environmentally friendly biomaterial derived from biomass and waste materials, has garnered significant interest and widespread adoption across diverse environmental applications owing to its versatile properties and potential for sustainable solutions. It is a porous carbonaceous material produced via thermochemical decomposition of feedstock in at limited or no oxygen environment. Pyrolysis is one of the promising methods for producing biochar, among other thermochemical methods such as hydrothermal carbonization, gasification, and torrefaction. However, conventional pyrolysis methods have limitations such as long process time, uneven heating, and low energy efficiency. Microwave technology has emerged as a promising method to overcome the limitations in conventional pyrolysis owing to its unique heating mechanism, providing volumetric heating to the feedstock in a shorter period [6]. Material with dielectric properties can absorb microwave irradiation, causing the molecules to rotate vigorously. This molecular friction and collision generate heat, effectively warming the material in a short period [7].

Biochar produced *via* microwave pyrolysis was reported to be effective in various types of wastewater, including heavy metals [8], dyes [9], nutrients [10], and pharmaceuticals [11].

However, pristine biochar produced *via* microwave pyrolysis exhibits reduced effectiveness against certain pollutants. This limitation is attributed to its lower surface area, porosity, and a limited range of functional groups within the biochar. Therefore, the activation of biochar has become a crucial step in improving the surface porosity and functionality of biochar in order to improve its efficiency in addressing various types of pollutants. For instance, activation with alkali such as sodium hydroxide produces biochar with higher dye removal efficiency (up to 45%) than pristine biochar [9]. Activation of biochar with chemicals and physical methods has also successfully improved the surface area of biochar up to two folds and eight folds, respectively [12]. It is thus important to investigate the effect of key parameters in microwave pyrolysis parameters on biochar production, activation methods, and the removal mechanisms for various types of water pollutants.

The literature available mostly focuses on the review of state-of-art of pyrolysis of various types of organic wastes [13], or specifically on certain types of waste, such as sewage sludge [14], pine waste [15], and tree residue [16], or the application of biochar in wastewater treatment [17-19]. Based on the current literature available, there appears to be a gap in research regarding the assessment of the effectiveness of biochar production *via* microwave pyrolysis and the activation of the resulting biochar for wastewater treatment. This review comprehensively examines the synergistic effects of biochar produced through microwave-assisted pyrolysis on wastewater treatment processes, aiming to elucidate the intricate relationship between the production method and the performance of the resulting biochar in wastewater remediation applications. The review commences with Section 2, which encompasses a bibliometric analysis of the subject matter. This is followed by Section 3 which presents various methods of microwave pyrolysis for biochar production. Section 4 focuses on the activation method for pristine biochar. Subsequently, Section 5 expounds on using engineered/modified biochar in diverse applications. Finally, Section 6 discusses the challenges and future prospects of the topic.

2. Bibliometric analysis

Microwave-assisted pyrolysis is promising in converting biomass and waste materials into value-added products such as biochar. Biochar can be used as an adsorbent for wastewater treatment owing to its porous structure, rich surface functional group, and low cost.

Bibliometric analysis has been used to study the research trend focusing on biochar production via microwave pyrolysis and its application in wastewater treatment. Scopus database has been selected for the analysis with twelve keywords (“microwave” OR "microwave-assisted" OR "microwave-assist" OR "microwave irradiation" AND “biochar” OR "activated biochar" OR "modified biochar" OR "engineered biochar" AND “wastewater” OR "wastewater treatment" OR "water pollution" OR "water remediation"). A total of 129 documents were obtained from 2014 to 2024. The peer-reviewed “article” and “review” in English were considered to improve the reliability of the analysis. Meanwhile, publications directly relevant to the research theme have been meticulously handpicked. As a result, 111 documents were selected for bibliometric analysis (92 research articles and 19 review articles). Network visualization was examined based on the co-occurrence of the keywords at least ten times, using VOSviewer (version 1.6.11) as shown in Figure 1. Among them, “biochar”, “adsorption” and “microwave irradiation” are the keywords showing the highest total link strength, which are 659, 558 and 479, respectively.

Five clusters were observed in Figure 1, indicating that there are five research hotspots for this topic, including (1) Biochar production via pyrolysis from biomass for wastewater treatment, (2) surface morphology studies of biochar produced via microwave pyrolysis of sewage, (3) chemistry and dye adsorption kinetics studies from wastewater, (4) Biochar and activated carbon production via microwave pyrolysis, and (5) adsorption of various types of pollutants with biochar produced from microwave pyrolysis.

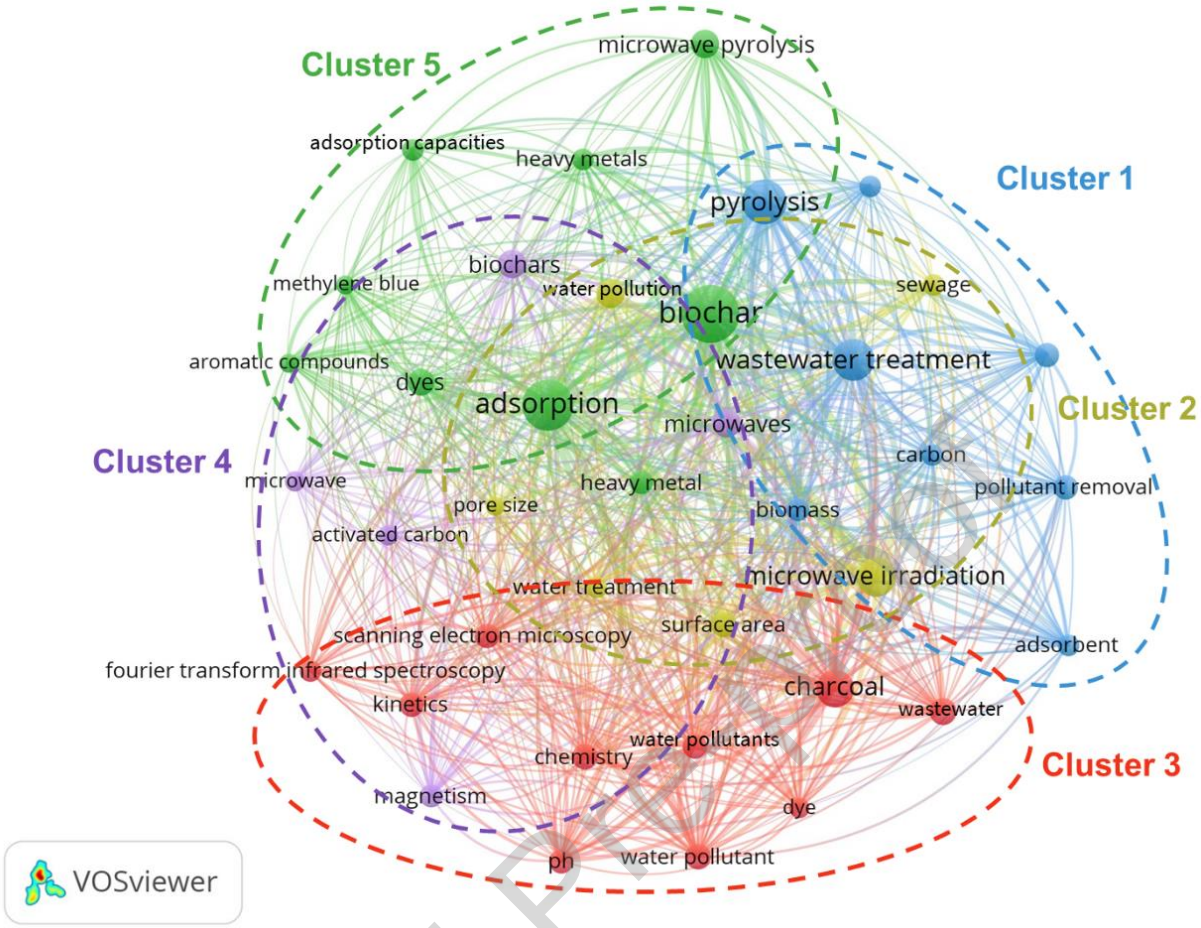

Figure 1. Bibliometric mapping of biochar production via microwave pyrolysis and its application in wastewater treatment over the past ten years (from 2014 to 2024) from 111 documents obtained from Scopus.

Figure 2 shows the research trend from 2020 to 2022. Before 2020, most research focused on producing biochar and activated carbon *via* conventional pyrolysis. The research utilizing microwave technology in pyrolysis bloomed in 2020, and the biochar produced has been used as an adsorbent in wastewater treatment. The research trend is slowly driven to study the adsorption of specific types of pollutants from wastewater, focusing on dyes such as methylene blue. Removal of heavy metals with biochar produced *via* microwave pyrolysis has become an increasingly significant concern in 2021. The effect of pH on the adsorption capacities has been highlighted in the second half of 2021, followed by studying the removal kinetics utilizing biochar as an adsorbent.

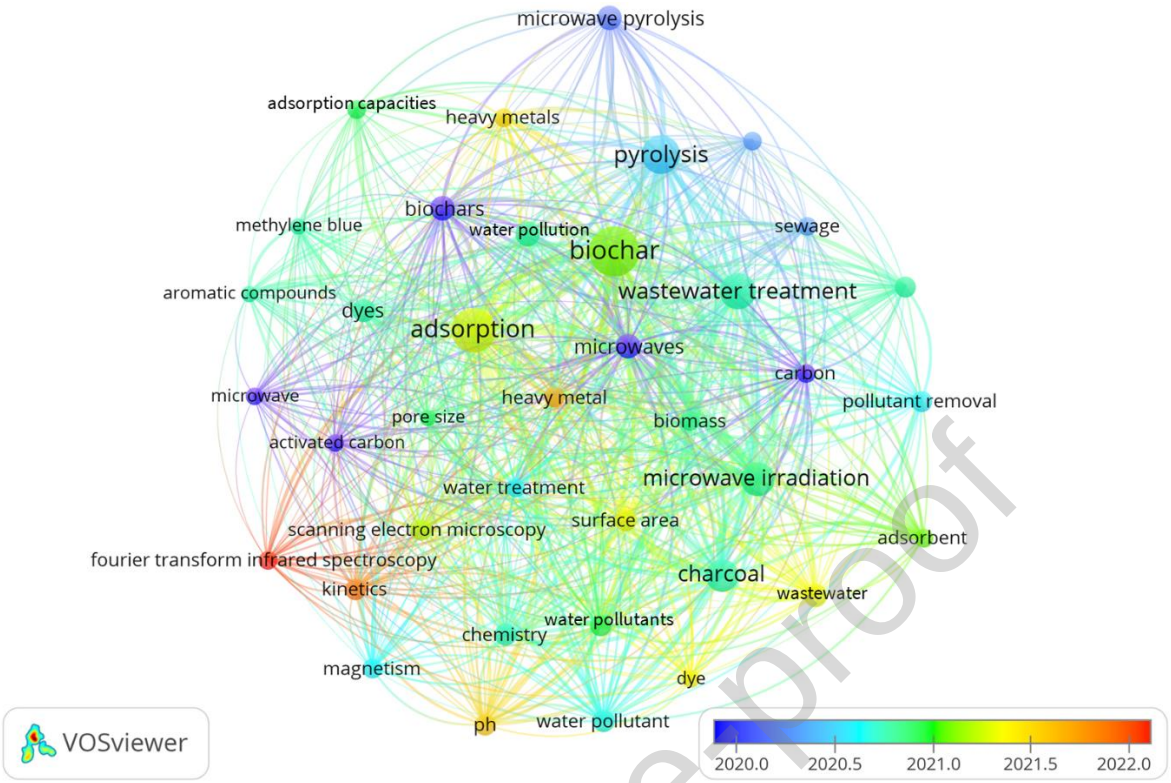

Figure 2. Bibliometric mapping with co-occurrence of keywords according to data from Scopus from 2020 to 2022.

The research cluster and trend have been studied from bibliometric analysis for the past ten years, showing that biochar produced *via* microwave-assisted pyrolysis has high potential in wastewater treatment. However, some research gaps need to be filled to maximize the potential of biochar produced *via* microwave-assisted pyrolysis in wastewater treatment. For instance, exploring the adsorption of emerging pollutants presents a novel research direction for engineered biochar. This is because it is more effective at adsorbing multiple pollutants simultaneously, in contrast to the current research, which primarily focuses on single-type pollutants. Meanwhile, studying the environmental impact and economic feasibility of the processes is essential before advancing to upscale and sustainable biochar production for use as an adsorbent in wastewater treatment.

3. Conventional and advanced pyrolysis for biochar production

3.1 Conventional microwave pyrolysis

Microwave-assisted pyrolysis harnesses microwave radiation to induce rapid thermal decomposition of biomass, yielding value-added byproducts. Distinguishing itself from conventional pyrolysis, microwave-assisted alternative offers superior heating rates, uniform thermal distribution, and enhanced heat transfer efficiency [20]. In this context, recent years have seen a surge in research efforts aimed at unveiling the potential of microwave-assisted pyrolysis for producing a high yield of engineered biochar with desirable properties, including high carbon content, optimized surface area and micropore structure that are favourable for adsorption of pollutants as summarized in Table 1. Several key factors have been identified as critical in determining the efficiency of microwave-assisted pyrolysis, including power [21, 22], reaction time [22, 23], temperature [24], and feedstock loading [24].

Understanding the dielectric properties of biomass materials, which are typically low loss (i.e., (low efficiency in converting microwave energy into heat) and mostly transparent to microwave radiation, is critical for assessing their behavior and energy absorption efficiency during microwave pyrolysis. This characteristic can be quantified by their dielectric constant and loss factor. The dielectric constant measures how much energy from an external electric field is stored in the material, while the loss factor indicates the ability of material to dissipate energy as heat [25]. During microwave pyrolysis, materials with higher dielectric loss factors are more effective at converting microwave energy into thermal energy, thus facilitating the pyrolysis process. However, most biomasses have low dielectric loss factor, posing a challenge for efficient heating. The addition of microwave absorbers, such as activated carbon, enhances the process by increasing the material's overall dielectric loss, thereby improving energy absorption and reducing the required microwave power and decarbonization temperatures [26, 27].

Microwave pyrolysis from various biomass, including empty fruit bunch [24, 28], oil palm shell [6, 23, 29], rice husk [10, 30], was examined and determined to be able to yield biochar production ranging from 40 to 70 wt.% An innovative self-purging microwave pyrolysis methodology by utilizing pyrolysis-generated gas has been demonstrated to further enhance the efficiency of the system by eliminating the need for an external nitrogen or air source and shorter processing time [29, 31]. Moreover, microwave-modified biochar produced

from further activation steps using CO_2 and potassium hydroxide (KOH) was reported to harvest improved and exceptional yields, which could amount to up to 92 wt.% [31].

Table 1. Conventional microwave-assisted pyrolysis of biomass for biochar production.

Biomass	Microwave optimal operating conditions	Biochar physical and thermochemical properties	Biochar elemental properties (TM: Total moisture; FC: fixed carbon; VM: volatile matter)	Biochar maximum yield	Ref.
Empty fruit bunch	• PW: 2600 W • FR: 2.45 GHz • t: 90 min • Feedstock loading: 1000 g • Air flowrate: 2 LPM • Temp.: 253 °C • Reactor: 10 L quartz chamber	• Particle size: 0.09 mm • High heating value (HHV): 6318 kcal/kg	• Proximate analysis - TM: 7.51% - Ash: 9.45% - FC: 32.04% - VM: 50.98% • Ultimate analysis - Carbon content: 62.75% - Oxygen content: 32.68%	50%	[28]
Medium density fiber board	• PW: 300 W • F: 2.45 GHz • t: 37.5 min • Feedstock loading: 20 g • N_2 flowrate: 0.09 LPM • Temp.: 200–300 °C • Reactor: 300 mL milestone ROTO SYNTH rotative solid phase microwave reactor • Microwave absorber: 3% activated carbon	Not reported	• Proximate analysis - TM: 1.6% - Ash: 4.2% - FC: 54.9% - VM: 38.5% • Ultimate analysis - Carbon content: 59.5% - Oxygen content: 27.5%	50%	[26]
Oil palm shell	• PW: 900 W • FR: 2.45 GHz • t: 20 min • Feedstock loading: 400 g • Temp.: 700 °C • Reactor: self-purging porcelain chamber (outer diameter: 150 mm; inner diameter: 145 mm; height: 100 mm)	• BET surface area: 410 m^2/g • Pore volume: 0.1948 cm^3/g • Pore size: 1.9 nm	• Proximate analysis - TM: 7 wt.% - Ash: 3 wt.% - FC: 66 wt.% - VM: 24 wt.% • Ultimate analysis - Carbon content: 78.5 wt.% - Oxygen content: 17.7 wt.%	45 wt.%	[29]
Rice husk	• PW: 500 W • FR: 2.45 GHz • t: 18 min • N_2 flowrate: 0.2 LPM • Reactor: Quartz tube • Microwave absorber: granular activated carbon, (rice husk: granular activated carbon = 5:1)	• BET surface area: 190 m^2/g • Pore size: 1.748 nm • pH: 8.75 • HHV: 25.46 MJ/kg	• Proximate analysis - TM: 5% - Ash: 31.05% - FC: 52.2% - VM: 18.5% • Ultimate analysis - Carbon content: 59.6% - Oxygen content: 39.45%	About 68%	[10, 30]

Olive pomace	• PW: 200 W • FR: 2.45 GHz • t: 1.5 min • Feedstock loading: 10 g • Reactor: Quartz tube (inner diameter: 35 mm)	• BET surface area: 392.3 m^2/g • Micropore volume: 0.15 cm^3/g	• Proximate analysis - TM: 4.7% - Ash: 9.8% • Ultimate analysis - Carbon content: 77.7% - Oxygen content: 19.4%	Not reported	[21]
Oil palm shell	• PW: 1000 W • FR: 2.45 GHz • t: 10 min • Amount: 70 g • Activation agent flowrate: 1 LPM steam • Temp.: 700 ℃ • Reactor: Open-top quartz funnel	• BET surface area: 539.80 m^2/g • Pore volume: 0.25 cm^3/g • Micropore volume: 0.22 cm^3/g • Mesopore volume: 0.03 cm^3/g • Pore size: 1.85 nm	• Proximate analysis - TM: 2.0 wt.% - Ash: 3.0 wt.% - FC: 73.0 wt.% - VM: 22.0 wt.% • Ultimate analysis - Carbon content: 81.9 wt.% - Oxygen content: 14.0 wt.%	45 wt.%	[6]
Oil palm shell	• PW: 1080 W • FR: 2.45 GHz • t: 30 min • Feedstock loading: 100 g • N_2 flowrate: 0.13 LPM • Reactor: Quartz tube (outer diameter: 35 mm; inner diameter: 28 mm; height: 500 mm)	BET surface area: 265.90 m^2/g	Not reported	64.58 %	[23]
Empty fruit bunch	• PW: 1000 W (pyrolysis and activation) • FR: 2.45 GHz (pyrolysis and activation) • t: 20 min (pyrolysis), 10 min (activation) • Feedstock loading: 800 g (pyrolysis), 100 g (activation) • Temp.: 600–700 ℃ (pyrolysis) • Reactor: 5 L self-purging porcelain chamber (pyrolysis), open top quartz reactor (activation) • Activation agent flowrate: 5 LPM CO_2	• BET surface area: 95.6 m^2/g • Micropore surface area: 60.0 m^2/g • Pore size: 3.9 nm	Proximate analysis - TM: 1.0% - Ash: 7.1% - FC: 69.3% - VM: 22.0%	92.0 wt.%	[31]

Empty fruit bunch in pellet and short fiber forms	• PW: 3380 W • FR: 2.45 GHz • t: 30 min • N_2 flowrate: 0.13 LPM • Temp.: 300 ℃ • Reactor: 14 L cylindrical alumina vessel	Not reported	• Proximate analysis - TM: 3.60% (pellet), 5.28% (fiber) - Ash: 26.30% (pellet), 16.82% (fiber) - FC: 60.58% (pellet), 64.52% (fiber) - VM: 9.52% (pellet), 13.38% (fiber) • Ultimate analysis - Carbon content: 56.86% (pellet), 59.83% (fiber) - Oxygen content: 38.51% (pellet), 34.97% (fiber)	47.4, wt.% (pellet), 50.0 wt.% (fiber)	[24]
Corn stalk	• PW: 500 W • t: 10 min • N_2 flowrate: 0.1 LPM • Reactor: Covered quartz crucible • Microwave absorber: activated carbon (corn stalk: activated carbon = 1:3)	• BET surface area: 325.23 m^2/g • Pore volume: 0.1814 cm^3/g • Micropore volume: 0.1420 cm^3/g • Pore size: 1.12 nm	Proximate analysis - VM: 10.58 wt.%	Not reported	[27]
Rice Husk	• PW: 1000 W • FR: 2.45 GHz • t: 5 min • Feedstock loading: 5 g • N_2 flowrate: 0.5 LPM • Reactor: Quartz tube (inner diameter: 20 mm; height: 300 mm)	• BET surface area: 172.04 m^2/g • Micropore surface area: 120.48 m^2/g • Pore volume: 0.1229 cm^3/g • Micropore volume: 0.063 cm^3/g	Ultimate analysis - Carbon content: 41.61 wt.% - Oxygen content: 29.56 wt. %	25.60 wt.%	[22]

"PW" refers to power, "FR" refers to frequency, "t" refers to time, "temp." refers to temperature.

3.2 Microwave-assisted co-pyrolysis

Co-pyrolysis of biomass with other feedstocks is proposed as an attractive approach for improving the quality of bioproducts. Hence, the realization of microwave-assisted pyrolysis has emerged to utilize a blended biomass feedstock over the last decade in the elucidation of its technical viability, as summarized in Table 2. It was revealed from the literature that co-pyrolysis with feedstocks having a high hydrogen-to-carbon ratio with hydrogen-deficient biomass were popular selections, such as co-pyrolysis of waste plastics [32-35] and algae [36, 37], since they were able to enhance the stability and properties of the resulting biochar. It also provided an opportunity for the valorization of waste materials that would otherwise be disposed of, contributing to the circular economy and reducing environmental impact, in which utilization of food waste [38-40], and optoelectronic sludge [41] was revealed to be plausible. The studies also demonstrated that co-pyrolysis enabled up until more than 70% enhancement in mass yield of biochar due to synergetic effects between the different feedstocks, leading to enhanced thermal decomposition and production, provided that the correct formulation and blending ratio were used [34, 38, 41]. Additionally, the emergence of microwave-assisted co-pyrolysis in the presence of a catalyst using potassium hydroxide (KOH) [33, 35, 42] and zirconium tetrabenzyl ($ZrBz_4$) [34] was reported to improve the yield of the biochar, which highlighted the potential of synergistic co- and catalytic pyrolysis for further exploration. The review also revealed that most of the co-pyrolysis studies had merely focused on improvement in biochar production with limited reports on the effect towards the resultant structural characteristics and properties, which also shed light on future works in this field.

Table 2. Microwave-assisted co-pyrolysis of various types of biomasses for biochar production.

Feedstock	**Microwave optimal operating conditions**	**Biochar physical and thermochemical properties**	**Biochar elemental properties (TM: Total moisture; FC: fixed carbon; VM: volatile matter)**	**Biochar maximum yield**	**Ref.**
Chlorella vulgaris (CV) algae and wood sawdust (WS)	• PW: 1000 W • FR: 2.45 GHz • t: 25 min • Feedstock loading: 30 g • Nitrogen flowrate: 0.3 LPM • Temp.: 675–750 ℃ • Microwave absorber: activated carbon or silica carbide (feedstock: absorber = 10:1) • Feedstock blending: 70% CV:30% WS with SC and 50% CV:50% WS with activated carbon	• High heating value (HHV): 23.03 MJ/kg (70% CV:30% WS with SC) • HHV: 27.10 MJ/kg (50% CV:50% WS with activated carbon)	Not reported	• 70% CV:30% WS = 31.1% (SC) • 50% CV:50% WS = 24.1% (activated carbon)	[36]
Food sludge (FS) and macadamia husk (MH)	• PW: 1520 W • t: 20 min • Feedstock loading: 320 mL • Temp.: 150 ℃ • Reactor: Teflon tube • Feedstock blending: 25% FS:75% MH	HHV: 19.6 MJ/kg	• Proximate analysis - Ash: 17% - FC: 25% - VM: 59% • Ultimate analysis - Atomic O/C ratio: 0.6 - Atomic H/C ratio: 1.8	About 75 wt.%	[38]
Optoelectronic sludge (OS) and *Mangifera indica* seeds (MIse)	• PW: 1520 W • t: 30 min • Feedstock loading: 320 mL • Temp.: 150 ℃ • Reactor: Teflon tube • Feedstock blending: 25% OS:75% MIse	HHV: 19.0 MJ/kg	• Proximate analysis - Ash: 3 wt.% - FC: 66 wt.% - VM: 24 wt.% • Ultimate analysis - Carbon content: 45.1 wt.% - Oxygen content: 39.6 wt.%	About 90 wt.%	[41]
Food waste (FW) and polyethylene (PE)	• PW: 900 W • FR: 2.45 GHz • Residence time: 7 s • Feedstock loading: 50 g • Temp.: 550 ℃ • N_2 flowrate: 0.2 LPM • Reactor: 2L quartz vessel • Microwave absorber: Flyash (feedstock: absorber = 20:1)	• BET surface area: 60 m^2/g (pre-modification), 1055 m^2/g (post-modification) • Pore size: about 25 nm	• Proximate analysis - Ash: 3.15 wt.% - FC: 79.9 wt.% - VM: 16.9 wt.% • Ultimate analysis - Carbon content: 63.8 wt.% - Oxygen content: 34.8 wt.%	About 45 wt.%	[40]

	• Feedstock blending: FW: LDPE = 8:1 • Modifier: 10% potassium phosphate (K_3PO_4)	(pre-modification), about 110 nm (post-modification)			
Food waste (FW) and low-density polyethylene (LDPE)	• PW: 800 W • Residence time: 7 s • Feedstock loading: 50 g • Temp.: 550 °C • N_2 flowrate: 0.25 LPM • Reactor: 2 L quartz vessel • Microwave absorber: biochar (7 wt.% in recirculation) • Feedstock blending: 87% FW:13% LDPE	• Pore size: 41 nm • HHV: 23.46 MJ/kg	• Proximate analysis - Ash: 3.3 wt.% - FC: 83.7 wt.% - VM: 13.0 wt.% • Ultimate analysis - Carbon content: 71.6 wt.% - Oxygen content: 23.6 wt.%	30 wt.%	[39]
Torrefied sawdust (TS) and polystyrene (PS)	• PW: 300 W • t: 10 min • Feedstock loading: 20 g • Temp.: 175 °C • Reactor: Quartz round bottom flask • Microwave absorber: graphite (feedstock: absorber = 1:1) • Feedstock blending: TS:PS = 1:1 • Catalyst: 15 g potassium hydroxide (KOH)	Not reported	Not reported	29.0 wt.%	[35]
Rice husk (RH) and polystyrene (PS)	• PW: 450 W • Feedstock loading: 20 g • Temp.: 600 °C • Reactor: 500 mL borosilicate flask • Microwave absorber: graphite (feedstock: absorber = 1:2) • Feedstock blending: RH:PS = 3:1 • Catalyst: 5 g potassium hydroxide (KOH)	Pore area: ~51 m^2/g	Ultimate analysis - Carbon content: 79.5 wt.% - Hydrogen content: 3.1 wt.%	34.1 wt.%	[33]
Chlorella vulgaris (CV) and rice straw (RS)	• Feedstock loading: 30 g • N_2 flowrate: 0.15 LPM • Reactor: Quartz crucible • Feedstock blending: CV:RS = 3:7	Not reported	Not reported	32.50%	[37]
Food waste	• PW: 800 W • FR: 2.45 GHz	HHV: 23.53 MJ/kg	• Proximate analysis - TM: 4.0 wt.%	61.25 wt.%	[32]

(FW) and low-density polyethylene (LDPE)	• t: 15 min • Residence time: 5 s • Feedstock loading: 50 g • Temp.: 500 ℃ • N_2 flowrate: 0.25 LPM • Reactor: 2 L quartz vessel • Microwave absorber: granular activated carbon (GAC) (6 wt.%) • Feedstock blending: 25% LDPE:75% FW		- Ash: 2.7 wt.% - FC: 85.3 wt.% - VM: 12.0 wt.% • Ultimate analysis - Carbon content: 69.9 wt.% - Oxygen content: 24.6 wt.%		
Paraffin wax (PW) and rice straw (RS)	• PW: 450 W • Feedstock loading: 10 g • Temp.: 600 ℃ • Reactor: 500 mL borosilicate flask • Microwave absorber: graphite (feedstock: absorber = 1:1) • Feedstock blending: PW:RS = 4:1 • Catalyst: 2 g potassium hydroxide (KOH)	Not reported	Not reported	29.2 wt.%	[42]
Bamboo (B) and low-density polyethylene (LDPE)	• t: 30 min • Temp.: 550 ℃ • Reactor: Quartz tube • Feedstock blending: B: LDPE = 1:3 • Catalyst: ZrBz (10 wt.% Zr, 3 g B char and 3 g ZSM-5)	Not reported	Not reported	73.96 wt.%	[34]

"PW" refers to power, "FR" refers to frequency, "t" refers to time, "temp." refers to temperature.

3.3 Catalytic microwave-assisted pyrolysis

Catalysts are essential in bio-oil upgrading as they can diminish undesired organic components such as oxygenated and nitrogen-containing compounds [43-45]. In microwave-assisted catalytic pyrolysis, the reactor configurations influence the performance of the microwave and the catalyst [46]. This is further supported by microwave heating in batch reactors provides limited penetration depth of microwaves. In contrast, reactors such as fluidized beds or rotary reactors enable a more uniform heat distribution. Hence, the synergistic effects of microwave heating and catalytic effects need to be understood. Table 3 summarizes the recent literature on engineered biochar from the catalytic microwave-assisted pyrolysis process. Despite numerous studies on catalytic pyrolysis for biochar production, few have concentrated on the microwave-assisted catalytic pyrolysis approach for generating engineered biochar using commercial catalysts (zinc chloride, iron (III) nitrate, sodium carbonate, bauxite, bentonite, clinoptilolite, potassium phosphate, activated carbon) [47-50], novel catalyst (Fe-modified *Choerospondias axillaris* seed-based biochar, and Fe modified rice husk bio-char) [51, 52], and renewable catalyst (activated carbon) [53, 54]. From these studies, the maximum yield of engineered biochar ranged from 36% to 79% when employing the catalytic microwave-assisted pyrolysis approach.

Table 3. Catalytic microwave-assisted pyrolysis approach for the production of biochar.

Biomass	Catalyst	Microwave optimal operating conditions	Biochar physical and thermochemical properties	Biochar elemental properties	Maximum biochar yield	Ref.
Wood waste	Zinc chloride and iron (III) nitrate	• PW: 1000–2000 W • Temp.: 400–800 °C	• BET surface area: 921.9–1556.7 m^2/g • Pore volume: 0.98 mL/g	X-Ray diffraction (XRD) analysis: Fe_3O_4, and ZnO	79%	[47]
Wheat straw	Activated carbon	• MW PW: 100 W, 200 W, 300 W, 400 W, 500 W, and 600 W • t: 5 min • Dinitrogen flowrate: 50 mL/min • Temp.:300–500 °C	• Specific surface area: 2.58–156.09 m^2/g • Pore volume: 0.0015–0.0790 cm^3/g	• Ultimate analysis: - Carbon content: 44.21–58.04% - Oxygen content: 19.81–40.95% - Nitrogen content: 1.26–1.42% - Hydrogen content: 1.61–5.13% • Atomic ratio: - H/C: 0.03–0.12 - O/C: 0.34–0.93	74.66 %	[53]
Wheat straw	Activated carbon	• PW: 100 W, 200 W, 300 W, 400 W, 500 W, and 600 W • t: 10 min • Biomass loading: 3 g • Nitrogen flowrate: 50 mL/min	• Particle size: 0.15–0.38 mm • Specific surface area: 1.22–312.62 m^2/g • Total pore volume: 0.0197–0.2218 cm^3/g • Micropore volume: 0.0005–0.1380 cm^3/g • Average pore diameter: 1.34–32.35 nm	• Volatile organic matter content: 9.8–66.4% • Acidic functional groups: 0.42–2.15 mmol/g		[54]
Switchgrass	Bauxite, bentonite, clinoptilolite, potassium phosphate, activated carbon	• PW: 750 W • FR: 2.45 GHz • t: 10 min • Biomass loading: 20 g • Nitrogen flowrate: 1.5 L/min • Temp.: 400 °C • Reactor: Quartz tube (44 mm inner diameter and 250 mm height)	• Particle size: 300–600 μm • BET surface area: 33.11–77.94 m^2/g • Average pore diameter: 2.15–11.81 nm • Micropore area: 10.89–48.9 m^2/g • Pore volume: 0.0091–0.0729 cm^3/g	• EDX analysis: potassium (K), phosphorus (P), and calcium (Ca).	43%	[48]

Switchgrass	Bentonite and potassium phosphate	• PW: 750 W • FR: 2.45 GHz • t: 30 min • Biomass loading: 20 g • Nitrogen flowrate: 1.5 L/min • Temp.: 300 °C and 400 °C • Reactor: Quartz tube (44 mm inner diameter and 250 mm height)	• BET surface area: 37.5–76.3 m^2/g • Micropore surface area: 329–402 m^2/g	• Proximate analysis - Ash: 46.07–59.68% • Ultimate analysis: - Carbon content: 25.86–35.78% - Oxygen content: 11.45–16.61% - Nitrogen content: 0.31–0.45% - Hydrogen content: 1.10–1.74% • Elemental analysis: - Potassium content:216.2–384.7 g/kg - Phosphorus content: 69.2–194.8 g/kg - Magnesium content: 4.53–12.97 g/kg - Calcium content: 14.21–23.32 g/kg - Sulphur content: 0.91–1.51 g/kg - Iron content: 0.30–16.65 g/kg - Manganese content: 0.07–0.09 g/kg - Zinc content: 0.03–0.05 g/kg - Copper content: 0.02 g/kg		[49]
Corn Stover	Sodium carbonate	• PW: 500 W, 700 W, 900 W • FR: 2.45 GHz • Biomass loading: 60 g • Nitrogen flowrate: 50 mL/min • Reactor: Cylindrical quartz reactor (14 cm diameter, 19 cm height)	• Particle size: 10 mm	• Proximate analysis - Ash: 10.11-24.88% - FC: 31.79-56.17% - VM: 19.74-58.10% • Ultimate analysis: - Carbon content: 58.41–70.53% - Oxygen content: 26.80–37.13%	~40%	[50]

				- Nitrogen content: 0.98–1.38% - Hydrogen content: 1.607–2.853%		
Corn cob	Fe-modified *Choerospondias axillaris* seed-based biochar	• PW: 800 W • FR: 2450 MHz • Temp.: 550 °C • Reactor: Quartz reactor	• BET surface area: 45.679–820.96 m^2/g • Micropore volume: 0.0145–0.418 cm^3/g	Not reported	46-52%	[51]
Torrefied corn cob	Fe modified rice husk biochar	• PW: 1 kW • FR: 2450 MHz • t: 20 min • Biomass loading: 10 g • Nitrogen flowrate: 1.5 L/min • Temp.: 500 °C • Reactor: Quartz reactor	• Particle size: 60 meshes	Not reported	36-42%	[52]

"PW" refers to power, "FR" refers to frequency, "t" refers to time, "temp." refers to temperature.

3.4 Microwave-assisted vacuum pyrolysis

Vacuum pyrolysis is defined as the altered form of conventional pyrolysis which involves conducting the process under vacuum conditions to replicate an inert atmosphere and eliminating the need to introduce inert gases such as nitrogen and argon. The term "vacuum" suggests that the pressure within the reactor system is reduced compared to atmospheric pressure. Usually, vacuum pyrolysis is conducted at a pressure ranging from 0.5 kPa to 50 kPa and moderate temperature between 400 °C and 600 °C [55]. Before pyrolysis, a vacuum pump was utilized to remove the air from within the reactor which aids in forming an inert atmosphere. Throughout the pyrolysis process, the volatile substances liberated will promptly disperse towards the vacuum pump due to the pressure contrast between the reactor and the pump.

In contrast to conventional pyrolysis, vacuum pyrolysis entails the reduction of energy consumption since there is no requirement for heating the inert gases. Moreover, the diminished biomass vapour pressure within the reactor may lower the degradation temperature of the biomass material which enables the pyrolysis to take place at a reduced temperature [56, 57]. The advantages of utilizing vacuum pyrolysis include lower production costs and the production of higher-quality biochar, characterized by a larger surface area and cleaner pores. This method also avoids combustion and prevents the reformation of volatiles through condensation on the surface of the biochar [58].

The drawbacks of vacuum pyrolysis include the production of a significant quantity of polycyclic macromolecular compounds, which impedes the breakdown into smaller molecular compounds. There are also challenges related to viscosity, where the raw bio-oil is high in viscosity, attributed to the densely linked polycyclic macromolecular compounds, which can result in inefficient fuel injection. Additionally, there is a risk of combustion occurring within the reactor, which could alter the intended process outcomes and potentially cause damage to the equipment [57, 59]. A few factors attributed to the risk of combustion are the occurrence of the residual oxygen in the vacuum pyrolysis reactor, the presence of volatile compounds in the feedstock, inadequate temperature control within the reactor, and the possibility of exothermic reactions taking place during the pyrolysis process.

Table 4 summarizes the recent literature on engineered biochar from the vacuum pyrolysis process. The literature reveals that various biomass types have been utilized in experimental studies employing the microwave-assisted vacuum pyrolysis approach for the production of engineered biochar, including cassava stem [60], palm kernel shell [61, 62], ashe

juniper [63]. From these studies, the maximum yield of engineered biochar ranged from 26% to 86% when employing the microwave-assisted vacuum pyrolysis approach.

Table 4. Microwave-assisted vacuum pyrolysis approach for the production of biochar.

Biomass	Microwave optimal operating conditions	Biochar physical and thermochemical properties	Biochar elemental properties (TM: Total moisture; FC: fixed carbon; VM: volatile matter)	Maximum biochar yield	Reference
Cassava stem	• PW: 550–750 W • FR: 2.45 GHz • t: 10 min • Pressure: 8–15 kPa • Reactor: 1 L Quartz reactor	• Particle size: 5 cm	• Proximate analysis - Ash: 0–9% - FC: 60–74% - VM: 19–36% • Ultimate analysis: - Carbon content: 51–57% - Oxygen content: 37–43% - Nitrogen content: 0–2% - Hydrogen content: 0–2%	77% (550 W) 73% (650 W) 70% (750 W)	[60]
Palm kernel shell	• PW: 750 W • t: 35 min • Pressure: 50 kPa • Reactor: Quartz pyrolysis reactor	• Particle size: 2–3 mm • Surface area: 270 m^2/g	• Proximate analysis - TM: 3% - Ash: 3% - FC: 84% - VM: 10% • Ultimate analysis - Carbon content: 70% - Oxygen content: 26% - Nitrogen content: 1% - Hydrogen content: 3% - Sulphur content: 0%	36% (550 W) 33% (650 W) 28% (750 W)	[61]
Palm kernel shell	• PW: 700 W • t: 35 min • Heating rate: 60 °C/min • Temp.: 607 °C	• BET surface area: 210 m^2/g • Pore volume: 0.10 cm^3/g • Mesopore volume: 0.07 cm^3/g • Pore size: 3.8 nm	• Proximate analysis - TM: 3% - Ash: 3% - FC: 85% - VM: 10% • Ultimate analysis - Carbon content: 79% - Oxygen content: 17%	84%	[62]

			- Nitrogen content: 1% - Hydrogen content: 3% - Sulphur content: 0%		
Ashe juniper	• PW: 350 W • t: 10 min • Biomass loading: 10 g • Pressure: 0.7 kPa • Heating rate: 20 °C/min • Biomass loading: 10 g • Temp.: 450 °C • Reactor: Glass flask	• Particle size: 2 mm	Ultimate analysis: - Carbon content: 46.5% - Oxygen content: 47.0% - Nitrogen content: 0.11% - Hydrogen content: 6.38% - Sulphur content: 0.00%	<50%	[63]

"PW" refers to power, "FR" refers to frequency, "t" refers to time, "temp." refers to temperature.

3.5 Environmental impacts and economic feasibility of microwave-assisted pyrolysis

Microwave pyrolysis offers a promising method for biomass conversion, demonstrating both environmental and economic benefits. The life cycle assessment (LCA) highlights a significant reduction in greenhouse gas emissions compared to conventional pyrolysis, with the global warming potential (GWP) ranging from 159 to 223 kg CO_2-eq per 1000 kg of switchgrass for microwave catalytic pyrolysis, compared to 737 to 1295 kg CO_2-eq for conventional pyrolysis [64-66]. This process also shows substantial energy savings, with drying and pyrolysis stages contributing 22% and 76% to total energy consumption, respectively. The ability of microwave pyrolysis to uniformly heat the biomass from the inside out increases the efficiency of the process, leading to higher yields of valuable products. For instance, optimal conditions can yield bio-oil production up to 37.4%, biochar at 33.6%, and gas at 29.0%[67].

The economic assessment of microwave pyrolysis reveals its potential profitability. The total production cost (TPC) ranges from 526 US$ to 1220 US$ per 1000 kg of dried biomass, with chemicals (e.g., K_3PO_4 and SiC) accounting for 37-55% of the TPC. The drying stage alone can contribute around 116 US$ to 244 US$ to the TPC [66]. Despite these costs, the economic feasibility of microwave pyrolysis is promising. Selling the products from microwave pyrolysis, such as bio-oil and biochar can lead to significant positive profits, making microwave pyrolysis an economically viable option for biomass conversion. Additionally, microwave pyrolysis reduces waste and provides a valuable method for managing biomass, such as mushroom spent compost, by converting it into renewable energy sources [67].

Beyond profitability, microwave pyrolysis offers additional benefits that enhance its appeal. The process not only generates valuable bio-oil and biochar but also contributes to waste management by converting agricultural and organic waste into useful products. This dual benefit of energy production and waste reduction makes microwave pyrolysis a compelling alternative to conventional biomass conversion methods. Moreover, the reduced environmental impact and energy consumption associated with microwave pyrolysis align with global sustainability goals, promoting the use of renewable energy sources and reducing dependence on fossil fuels. These findings underscore the potential of microwave pyrolysis in achieving sustainable and cost-effective bio-oil and biochar production, making it a viable and environmentally friendly alternative for biomass conversion.

4. Activation processes to produce engineered biochar

The application of biomass as feedstock in microwave-assisted pyrolysis has been impeded by its complex structure, reducing the efficiency of the process and consequently affecting the yield and quality of the pyrolytic products [68]. Hence, post-pyrolysis activation of the pristine biochar is necessary, either by physical or chemical means, to further enhance its pore structure, increase its specific surface area, and modify the functional groups on its surface. This approach is aimed at enhancing the adsorption capabilities of biochar in wastewater treatment, resulting in what is referred to as 'engineered biochar' [10, 69]. Therefore, activation is essential in strategies for preparing engineered biochar.

4.1 Physical activation of engineered biochar

Physical activation is known for producing engineered biochar without chemicals, which in turn prevents contamination by chemical impurities [70-73] (Figure 3). This process is relatively simple and produces engineered biochar in a more straightforward manner than other activation methods, making it highly suitable for large-scale applications for wastewater treatment [74, 75]. It is worth noting that in the production of engineered biochar, the activation process can be placed before and after pyrolysis. However, it is worthwhile to consider that high activation temperature and long activation time may lead to higher operational costs for physical activation than chemical activation [76].

Engineered biochar is produced through the combination of pyrolysis and biochar activation. There are two methods to achieve this: the "one-step method" and the "two-step method". The former involves performing pyrolysis and activation simultaneously, while the latter involves performing pyrolysis first, followed by activation. During the pyrolysis process, an activation gas such as steam or CO_2 is added, and the pyrolysis duration is increased to achieve activation simultaneously with pyrolysis. This integrated production process simplifies the production process of engineered biochar and allows large-scale operations, hence effectively reducing production costs. Lam et al. [6] have introduced an innovative and efficient biochar production technique. The traditional two-step process of pyrolysis followed by steam activation has been replaced by a single-step process that involves microwave steam activation. This new technique has several advantages over the traditional method, including a higher heating rate through microwave-assisted high-temperature steam activation and shorter processing times. As a result, higher engineered biochar recovery rates can be achieved, making

it a promising method for producing high-quality engineered biochar [6]. Yek et al. [31] employed a microwave pyrolysis system to pyrolyze empty fruit bunches to produce engineered biochar. Subsequently, microwave-assisted CO_2 was applied for activation to prepare the engineered biochar specifically for landfill leachate treatment. The specific surface area of the activated engineered biochar increased 23-fold (95.6 m^2/g) compared with the engineered biochar (4.1 m^2/g), providing more active adsorption sites for proteinaceous organic matter in landfill leachate.

The one-step engineered biochar production process is simple, aligning well with the market demand for economical and high-yield solutions required for wastewater treatment applications [77]. While one-step engineered biochar production offers cost and simplicity advantages, there is still room for improvement in developing activation methods, and further research needs to be directed toward the ability to obtain engineered biochar through simpler processes that can more efficiently adsorb water pollutants [78]. The two-step preparation of engineered biochar, involving a separate activation step, has demonstrated superior activation effects [79]. This approach produces a higher yield of engineered biochar with larger specific surface areas and pore volumes (Table 4) [80]. Therefore, strategically engineered biochar using a two-step preparation has advantages in water pollution treatment efficiency.

Table 4 Effect of activation strategy on the specific surface area of engineered biochar

Activation strategy	Specific surface area (m^2/g)	Ref.
One-step	309.2	[81]
One-step	158.5–305.1	[31]
One-step	679.22	[6]
Two-steps	881	[82]
Two-steps	1036	[83]
Two-steps	590	[84]
Two-steps	1300	[72]

Steam [84] and CO_2 [72, 85] can effectively activate the pristine engineered biochar. However, it is worth noting that different conditions and processes may produce different qualities of engineered biochar [82]. Regarding physical activation during biochar preparation, Colomba et al. [72] proposed that the activation process deepens biochar pores instead of

widening them. Therefore, it is imperative to carefully explore appropriate activation conditions and select suitable activation strategies for preparing engineered biochar through physical activation. These may include maintaining sufficient temperature and gas flow as well as employing auxiliary methods such as microwave and ultrasound [46, 86] (Figure 3b and 3c). Shan et al. [87] employed a microwave-assisted steam activation technique to produce microwave-engineered biochar as an adsorbent for mercury ion adsorption. The study reveals that the high ash content in biochar obstructs pore structure development. However, the microwave and steam activation procedure diminish the ash content and volatiles on the surface of biochar, leading to a significant increase in the specific surface area (57.047 m^2/g–189.804 m^2/g). This affirms that microwave treatment refines the pore structure during the activation phase, providing a higher specific surface area for mercury ion adsorption.. Zheng et al. [83] utilized microwave-induced CO_2 physical activation method to activate biochar. The research aimed to optimize the activation parameters to produce high-quality engineered biochar with a specific surface area of 1036 m^2/g. After conducting experiments, the team identified 90 min of activation time, 980 °C of activation temperature, and 300 mL/min of CO_2 flow rate as the optimal activation parameters to produce high-quality engineered biochar with a large specific surface area.

When it comes to biochar activation, the use of CO_2 as an activating agent is known to produce higher yields and specific surface areas than steam activation. The advantage of CO_2 activation also lies in its ability to operate at lower reaction temperatures, thus reducing energy consumption [31]. However, steam activation promotes mesopore formation, leading to larger mesopore volumes. As a result, when choosing between steam and CO_2 activation, the structure of the adsorbed material needs to be considered. Steam activation benefits the adsorption of certain macromolecular substances. On the other hand, the higher specific surface area achieved through CO_2 activation can lead to higher adsorption capacity and micropores for small molecules [87]. Additionally, steam-activated biochar is alkaline and has a low proportion of acid-oxygen functional groups on its surface, which is crucial for acidic substance adsorption [84]. Regardless of the activation strategy employed, factors such as activation time, temperature, and gas flow rate are critical to producing engineered biochar. Recent advancements in physical activation techniques have optimised the process and reduced the required temperatures. This development can potentially improve the efficiency and cost-effectiveness of producing engineered biochar. Consequently, this opens up the possibility of

using engineered biochar to meet the increasing demands for environmental wastewater treatment on a larger scale [88, 89].

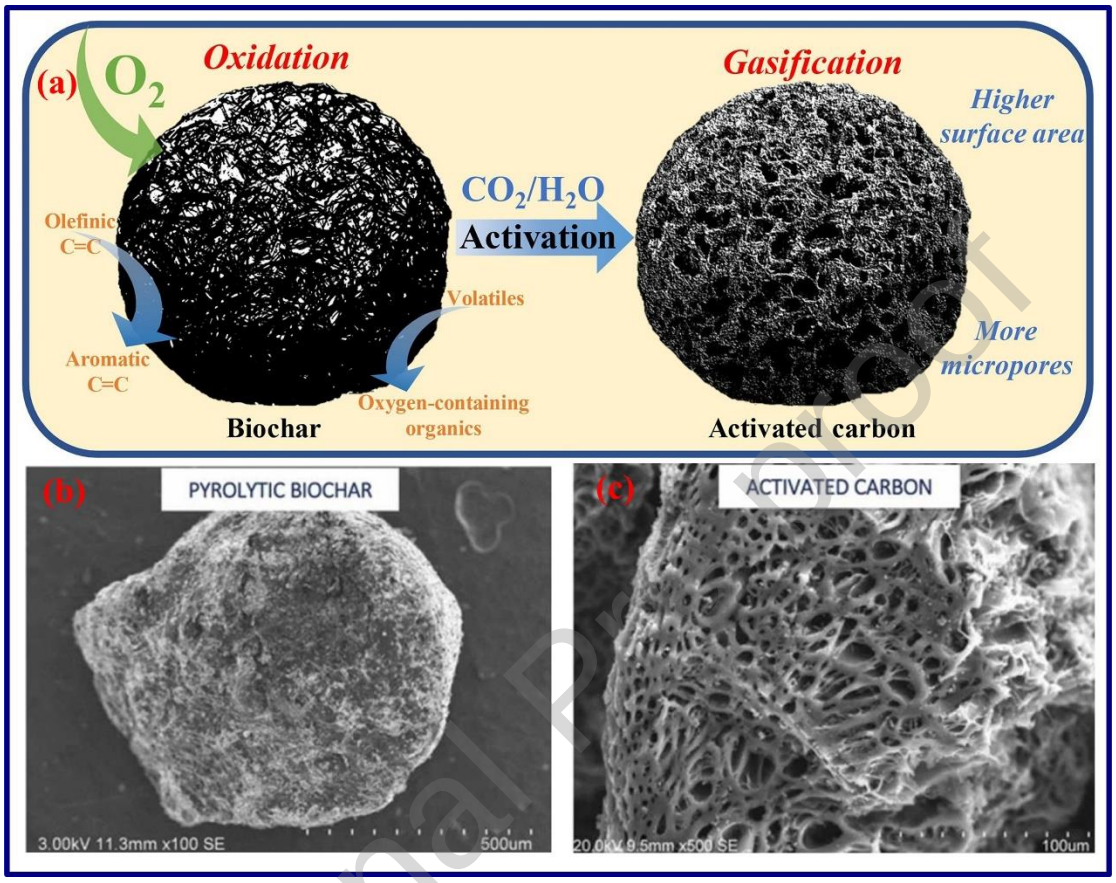

Figure 3. (a) Carbon dioxide/steam activation of biochar, reprinted from Li et al. [73] with the permission from Elsevier, Copyright © 2024. License number: 5758450718074, (b) Inactivated biochar, and (c) CO_2 activated biochar, both reprinted from Colomba et al. [72] with the permission from Elsevier, Copyright © 2022. License number: 5779130066288

4.2 Chemical activation of engineered biochar

Chemical activation is a process that utilizes acidic or alkaline solutions to erode biochar, resulting in the formation of new cavities and expansion of pores through reactions with biochar [90, 91]. This process also increases the specific surface area and functional groups, such as oxygen or nitrogen-containing groups [92]. The additional functional groups on biochar improve the adsorption of polar compounds including benzene, toluene, and phenol, making it a more effective adsorbent of organic pollutants in aqueous environments such as oil

spills [93, 94]. Chemical activation is a viable alternative to physical activation, as it facilitates pore formation through chemical reagents at lower temperatures. This eliminates the need for higher activation temperatures, thereby increasing the efficiency of producing high-quality biochar [95]. Unlike physical activation, which is typically performed after pyrolysis, chemical activation can be conducted before or after, resulting in different biochars with specific engineered properties based on the chosen strategy. Wang et al. [96] used microwave-assisted phosphoric acid activation to prepare engineered biochar with a high BET surface area (1074 m^2/g), demonstrating good adsorption for acid red 18 (95.22 mg/g). However, compared to ammonium chloride and ammonium acetate (134.17 mg/g, 111.94 mg/g), the adsorption of organic dyes (indigo and haichang blue) was reduced due to fewer functional groups in the biochar activated before pyrolysis. Nair et al. [97] have developed an optimized method for producing activated biochar with excellent pore structure and effective dye adsorption capabilities. The process involved soaking biochar in hydrogen peroxide (H_2O_2) for 24 h followed by microwave pyrolysis at 600 W. The resultant activated biochar demonstrated a remarkable micropore area of 275 m^2/g, a pore volume of 0.13 cm^3/g, and an average pore diameter of 3.5 nm.

In general, activation before pyrolysis can achieve a better degree of carbonization due to the destruction of the biomass structure by chemical activation, making the subsequent pyrolysis cracking more complete. This effectively reduces the required pyrolysis temperature but may result in the loss of some chemical functional groups, which weaken the subsequent adsorption of organic pollutants. On the other hand, post-pyrolysis activation can result in a better pore structure in the biochar. This is because the biomass structure and more functional groups are retained after pyrolysis, which positively impacts polar compound adsorption. Acid can be used as a chemical activator to effectively remove impurities on the biochar surface and better penetrate the pores of the biochar structure. This allows the chemical reaction to proceed more thoroughly, thereby increasing the number of micropores and mesopores on the biochar [98]. In a study by He et al. [81], biochar production through steam activation, carbon dioxide activation, and sulfuric acid activation was compared. The results showed that biochar produced through acid activation had the largest specific surface area of 316.7 m^2/g, indicating the presence of numerous pores within the biochar. On the other hand, steam activation resulted in biochar with the lowest surface area of 53 m^2/g, which could be attributed to fewer internal pores. Interestingly, the biochar obtained through acid activation had a smaller surface area of 53 m^2/g than steam activation, which showed a surface area of 65.1 m^2/g. These findings

suggest that acid activation promotes the development of internal pores in biochar rather than the etching of the external surface [99].

Furthermore, the acid activation strategy can facilitate the incorporation of surface functional groups into engineered biochar such as carboxyl groups, amino groups, and other oxygen-containing groups to enhance the adsorption of polar substances (such as dyes) [100]. Compared to non-oxygen-containing acids, oxygen-containing acids can introduce more functional groups, enhancing engineered biochar adsorption [101]. Villota et al. [102] explored the effects of phosphoric acid (H_3PO_4) concentration (56.5%) and microwave power (650 W). The study revealed that excessive use of phosphoric acid (H_3PO_4) can lead to a longer pyrolysis process time, which reduces process efficiency. This is because an excess of phosphoric acid (H_3PO_4) can result in poor microwave absorption by the biomass and phosphoric acid mixture. Furthermore, the conversion of phosphoric acid (H_3PO_4) into its anhydride P_2O_5 requires higher activation energy, which prolongs the pyrolysis process time. Lonappan et al. [103] thoroughly analyzed the toxicological and environmental problems caused by the acute toxicity and harmful effects of mineral acids (e.g., volatilization of hydrochloric acid and nitric acid) and proposed an organic acid activation strategy to modify the biochar surface functional groups. When comparing the activation effects of different organic acids, citric acid was proposed as an effective organic acid for efficient functionalization of the biochar surface with carboxylic group (-COOH).

The utilization of alkali for activation aims to increase the number of functional groups and develop the internal pores of biochar [104, 105]. Compared with acid activation, alkali activation emphasizes the pores development to obtain a larger specific surface area and optimum pore structure, which is more effective for the adsorption of inorganic pollutants and small-volume organic pollutants such as heavy metals and polycyclic aromatic hydrocarbons [106]. Zhang et al. [107] compared the activation effects of potassium hydroxide (KOH), potassium acetate (CH_3COOK) and the physical activator of CO_2 on biochar. It was concluded that potassium hydroxide (KOH) can create an ideal pore structure with a large specific surface area on biochar. However, alkali-activated biochar shows fewer oxygen-containing functional groups than physically-activated biochar (Figure 4a). Chen et al. [108] investigated using potassium hydroxide (KOH) as an activator to enhance biochar adsorption capacity. By replacing some of the carbon in biochar with potassium hydroxide (KOH), a series of reactions occurred and released gases such as hydrogen, water vapour, and carbon dioxide, forming small pores in the biochar structure. The prepared biochar showed a significant improvement in the

adsorption of heavy metal ions, phosphorus compounds, and other nonpolar molecules, demonstrating six times higher adsorption capacity than biochar prepared without activation. Zhang et al. [109] explored multi-activator mixture ($MnCl_2$/KOH) activation to prepare highly porous biochar. The surface area of biochar obtained by dual chemical reagent activation was higher than that of chemical activation with a single reagent (Figure 4b). This provides a new idea for chemical activation through appropriate combinations of different activators. The activation mechanism of potassium hydroxide (KOH) and potassium bicarbonate (K_2CO_3) has been revealed by many studies [110, 111] (Eq. 1–4):

$$2KOH \rightarrow K_2O + H_2O \quad (1)$$

$$C + H_2O \rightarrow H_2 + CO \quad (2)$$

$$CO + H_2O \rightarrow H_2 + CO_2 \quad (3)$$

$$K_2O + CO_2 \rightarrow K_2CO_3 \quad (4)$$

In a study conducted by Shi et al. [112], biochar was prepared and activated from microalgae using potassium hydroxide (KOH). A microwave was employed to facilitate the insertion or migration of charged metal atoms into the carbon structure of engineered carbon, resulting in the formation of pores on the surface of activated carbon. This in turn increased the surface area and total pore volume of engineered carbon [90, 113]. The prepared engineered biochar exhibited a high specific surface area (510.3 m^2/g) and pore volume (0.33 cm^3/g). Alkaline activation of biochar increased its positive charge, enhancing its ability to adsorb negatively charged pollutants such as humus and protein in water [114].

In summary, microwaves have proven to effectively promote the activation reaction between the activator and biochar through rapid heating [115]. However, it is essential to optimize the process conditions to prevent pore damage caused by the prolonged microwave irradiation time. When preparing microwave-assisted activated biochar, a physical activation strategy is preferred as it reduces activation costs due to the lower price of activation gas and comparatively simpler processing steps. The physical activation process tends to produce desirable pores for the adsorption of small molecular substances such as inorganic pollutants and small-molecule organic matter. Physical activation can obtain engineered biochar with fewer functional groups and a more complete carbonization degree [116, 117]. Although microwave heating can somewhat reduce these costs, physical activation strategies still involve operational costs due to the high activation temperature and long activation time involved.

Chemical activation processes employ diverse reagents to tailor specific pore structures and surface functional groups in biochar, with the choice of reagent driven by the desired final properties of the activated material [114, 118]. Alkali activation predominantly promotes pore development [119], with potassium hydroxide (KOH) notably enhancing micropore formation compared to other reagents. However, physical activation necessitates a higher activation temperature to break down oxygen-containing functional groups in the carbon, thereby disadvantaging it for adsorbing large organic compounds in water compared to chemical activation methods [120]. Acidic activators, such as phosphoric acid and chlorine-based metal salts, mainly stimulate the growth of larger mesopores, resulting in a lower specific surface area through acid activation than alkali activation. Nevertheless, acid activation tends to retain more active functional groups, facilitating the adsorption of macromolecular organic matter [121]. Thus, in the context of engineered biochar production, the selection of activation methods should be tailored to the intended application. Different activation techniques should be chosen based on the specific requirements of the usage sites.

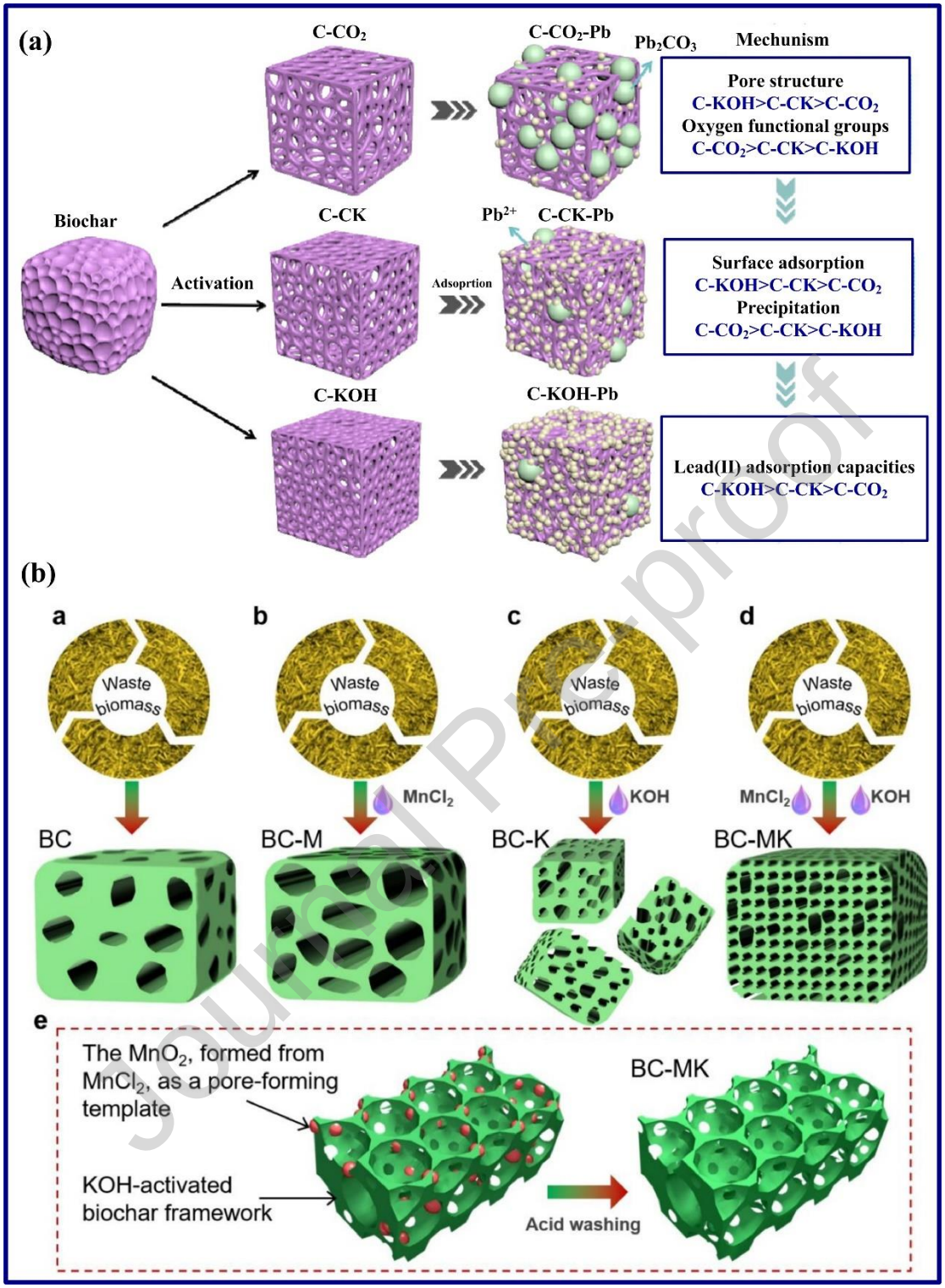

Figure 4. (a) Advantages of KOH chemical activation reported by Zhang et al. [107], reprinted with the permission from Elsevier, Copyright © 2024. License number: 5758451160125, (b) $MnCl_2$/KOH dual chemical activation strategy reported by Zhang et al. [109], reprinted with the permission from Elsevier, Copyright © 2023. License number: 5779121388817

5. Biochar application in wastewater treatment

5.1 Heavy metal wastewater treatment

Heavy metal waste is the excessive discharge of metallic elements that are poisonous or detrimental to the environment and public health [122]. Heavy metals are among the most hazardous pollutants in industrial effluent due to their toxicity and environmental persistence. Toxic pollutants containing heavy metals such as lead (Pb), cadmium (Cd), and mercury (Hg) are frequently discovered in industrial effluent [123]. Several pathways such as industrial discharges, agricultural runoff, and improper disposal of products containing heavy metals, can introduce these metals into the environment. Exposure to heavy metals has been linked to a range of serious health issues including cancer, kidney damage, and neurological diseases [124].

The use of biochar has shown promise in the remediation of heavy metal contamination in wastewater, providing an economical and environmentally friendly alternative. The adsorption of heavy metals by biochar via physical and chemical mechanisms has been extensively studied [125]. A large surface area and the porous structure of biochar are responsible for its ability to adsorb heavy metals [126]. The efficiency of biochar in eliminating heavy metals from wastewater has been shown in numerous research [127]. For example, Qi et al. [53] studied the effectiveness of microwave biochar prepared from wheat straw for the adsorption of heavy metals like Pb(II), Cd(II), and Cu(II). The results showed that at a power of 500 W, the microwave biochar had the highest specific surface area (156.09 m^2/g) and total pore volume (0.0790 cm^3/g). The wheat straw biochar produced using this method had maximum adsorption capacities of 139.44 mg/g, 52.92 mg/g, and 31.25 mg/g for Pb(II), Cd(II), and Cu(II), respectively. It was found that the ideal pH range for heavy metal elimination was between 5 to 8. Chen et al. [128] investigated the potential of biochar produced from microwave pyrolysis of rape stalks for removing Cd(II) from contaminated water. The biochar had an adsorption capacity of 53.17 mg/g and closely followed the Langmuir and pseudo-second-order models. The investigation of the adsorption mechanisms revealed that Cd-π interaction was the primary mechanism responsible for Cd(II) removal which accounted for 56.22%. Furthermore, biochar could be easily regenerated for reuse and applied to column adsorption. Meanwhile, Qin et al. [129] reported microwave-heated $MgCl_2$-modified biochar derived from cotton stems achieved a high adsorption capacity of 178.17 mg/g of Cd(II) at pH 6 but a different mechanism, which were cation exchange and precipitation.

5.2 Pharmaceutical wastewater treatment

Pharmaceutical waste consists of various elements, including contaminated vials, packing materials, and medications that have expired or were not utilized. Improper disposal of certain chemical compounds poses a severe threat to the environment and can endanger the health of both humans and animals. For instance, antibiotics and hormones are known to significantly impact aquatic ecosystems when they enter waterways [130]. Additionally, the handling and disposal of antineoplastic drugs, which are commonly used in cancer treatment, require adequate safety measures to prevent harmful effects on anyone exposed to them. It is crucial to note that discarding expired or unnecessary medications in regular trash or flushing them down toilets can contaminate soil and water. Moreover, pharmaceutical chemicals are increasingly found in wastewater due to their widespread usage [131]. These substances may be harmful to aquatic habitats and species. Pharmaceutical chemicals are emerging pollutants in wastewater, endangering aquatic ecosystems and public health [132].

The high surface area and porosity of biochar have demonstrated potential in removing pharmaceuticals from wastewater [133]. Pharmaceutical compounds are adsorbed onto biochar by several methods such as electrostatic interactions, hydrogen bonding, and π-π interactions [134]. Several studies have demonstrated the effectiveness of biochar in removing pharmaceuticals from wastewater. For example, Qin et al. [129] studied the effectiveness of microwave-heated $MgCl_2$-modified biochar derived from cotton stems for adsorbing tetracycline. The adsorption isotherm analysis indicated that the adsorption capacities of tetracycline was 201.85 mg/g, at pH values of 5. The mechanism of adsorption for tetracycline was electrostatic attraction and π-π interaction. The adsorption efficiency of the biochar was influenced by factors such as the concentration of pharmaceutical compounds in solution, pH, and the characteristics of the biochar.

5.3 Dye wastewater treatment

Dye waste is a form of chemical waste produced during the colouration of textiles, paper, plastics, and other products. The textile, paper, and leather industries are among the many industries that widely employ dyes, and as a result, wastewater containing dyes is frequently discharged into the environment. Azo dyes, reactive dyes, and dispersion dyes are commonly used in these industries. Due to their high toxicity, durability, and ability to collect

in aquatic organisms, these dyes pose significant environmental dangers. As a result, these substances can be highly hazardous and present significant challenges to wastewater treatment.

The adsorption capacity and large surface area of biochar have made it a viable material for the treatment of dye wastewater [135]. The carboxyl, hydroxyl, and phenolic groups on the biochar surface are important. These functional groups can form complexes with dye through surface complexation mechanisms, ion exchange, and electrostatic interactions. The porous structure of the biochar offers a multitude of binding sites for dye molecules, making it easier to remove them from wastewater. Banana peel biochar generated via microwave-assisted pyrolysis was examined to adsorb malachite green [136]. The adsorption capacity of the biochar produced at 500 °C and 900 °C was the highest at 1790.30 mg/g and 2297.83 mg/g, respectively. Remarkably, the banana peel biochar maintained its exceptional adsorption capacity of 400 mg/g to 450 mg/g for malachite green after five regeneration cycles. Another study by Jabar et al. [137] indicated that plantain leaf biochar activated with microwave phosphoric acid is an effective mesoporous-engineered biochar with a BET surface area of 986.35 m^2 g^{-1} and an average pore diameter of 44.13 Å. The engineered biochar adsorbed maximum malachite green (> 99%) under specific conditions such as pH of 8.0, initial malachite green concentration of 50 mg/L, adsorbent dosage of 0.2 g/L, contact time of 80 min, and temperature of 301 K. Additionally, the engineered biochar exhibited excellent regeneration (> 97%) even after five regeneration cycles, demonstrating its potential as a sustainable green adsorbent. Therefore, biochar for dye wastewater treatment offers a cost-effective and environmentally friendly solution.

5.4 Aquaculture Wastewater Treatment

Aquaculture waste refers to the waste and by-products produced by aquaculture practices such as fish farming, prawn farming, and other forms of aquatic farming. These wastes include uneaten feed, faeces, chemicals, antibiotics, and organic and inorganic components. As the aquaculture industry grows, its effluent contains high concentrations of pollutants, organic matter, and nutrients. Conventional fish meals have been linked to several detrimental environmental impacts. These include the contamination of water sources, the proliferation of algal blooms and other pathogenic organisms, as well as the escalation of chemical and biological oxygen demands. These effects can potentially lead to a severe oxygen deficiency crisis, causing significant harm to aquatic life and the broader ecosystem.

Biochar has recently emerged as a potential treatment material for aquaculture effluent. Specifically, it has been demonstrated that biochar produced from palm waste can efficiently remove ammoniacal nitrogen from aqueous solutions. Su et al. [138] investigated the potential of biochar produced via microwave pyrolysis in aquaculture wastewater treatment. It was found that the BET surface area of biochar produced from palm kernel shell reaches 419 m^2/g, and has successfully removed 67% of ammonia and 68% of total suspended solids from African catfish culture water. Besides removing pollutants, the biochar provided surface area for the attachment of nitrifying bacteria that converted ammonia into nitrate, thereby increasing the nitrogen uptake and enhanced the growth of lettuce up to 0.0562 % per day. Table 5 shows the wastewater pollutants adsorption using microwave-irradiated biochar under different experimental conditions.

Table 5. Wastewater pollutants adsorption using biochar produced via microwave-assisted pyrolysis under different experimental conditions.

Source of biochar	Synthesis method	Type of pollutant	Operating conditions						Ref.
			Adsorbent dose (mg/mL)	Temperature (°C)	Time (hour)	pH	Agitation speed (rpm)	Absorption capacity (mg/g)	
Heavy metal adsorption									
Cotton stem	Magnesium chloride ($MgCl_2$) Temp. = 700 °C t = 30 min *oxygen-free environment	Cd^{2+}	1.0	-	-	5	-	178.17	[129]
Rape stalk	Temp. = 600 °C Nitrogen (N_2) atmosphere	Cd^{2+}	1.0	-	-	5	300	53.17	[128]
Alkali lignin	t = 10 min N_2 flow = 200 mL/min PW = 1500 W Temp. = 400 °C Hydrochloric acid (HCl)	Cu^{2+}	0.2	45	1	5	150	492.75	[139]
Water hyacinth	Potassium hydroxide (KOH), Iron chloride hexahydrate ($FeCl_3 \cdot 6H_2O$), Sodium acetate (CH_3COONa), Sodium citrate ($Na_3C_6H_5O_7$), and Ethylene glycol ($C_2H_6O_2$) Temp. = 700 °C t = 2 h in nitrogen (N_2)	Cr^{6+}	0.5	25	2	2.5	-	202.61	[140]
Wheat straw	PW = 500 W N_2 flow = 50 mL/min	Pb^{2+}	0.025 g	25	48	6	250	139.44	[53]
		Cd^{2+}	0.025 g	25	48	6	250	52.92	
		Cu^{2+}	0.025 g	25	48	5-6	250	31.25	
	Hydrogen peroxide PW = 100–500 W N_2 flow = 50 mL/min	Pb^{2+}	0.5	25	48	6	250	190.2	[141]
		Cd^{2+}						57.6	
		Cu^{2+}						65.2	
Pharmaceutical residue adsorption									
Coconut shell	Potassium hydroxide (KOH) and potassium chloride (KCl)	Tetracycline	0.01 g	35	6	7	100	1033.06	[142]

	Temp. = 1000 °C t = 20 min in nitrogen (N_2)								
Water hyacinth	Potassium hydroxide (KOH), Iron chloride hexahydrate ($FeCl_3 \cdot 6H_2O$), Sodium acetate (CH_3COONa), Sodium citrate ($Na_3C_6H_5O_7$), and Ethylene glycol ($C_2H_6O_2$) Temp. = 700 °C t = 2 h in nitrogen (N_2)	Tetracycline	0.5	25	3.33	4	-	202.62	[140]
Sewage sludge	Zinc chloride ($ZnCl_2$) concentration = 1.5 mol/L t = 8 min PW = 915 W	Sulfamethoxazole	2.0	25	24	3	210	50.6	[143]
Orange peel waste	Sulphuric acid (H_2SO_4), Iron chloride ($FeCl_3$) in hydrochloric acid (HCl), sodium sulphite (Na_2SO_3), ammonia (NH_3), calcium chloride ($CaCl_2$) t = 160 s followed by iron (II, III) oxide (Fe_3O_4) via the reduction-precipitation	Sulfamethoxazole	1.0 g	25	24	4	150	120	[144]
Cotton stem	Magnesium chloride ($MgCl_2$) Temp. = 700 °C t = 30 min *oxygen-free environment	Tetracycline	1.0	-	-	6	-	201.85	[129]
		Dye adsorption							
Oil palm shell	FR = 2450 MHz Temp. = 700 °C Time = 20 min	Methylene blue	0.2 g	Room temperature	-	-	200	20.00	[145]
Phragmites australis	Ammonium acetate ($C_2H_7O_2N$) PW = 700 W t = 15 min Nitrogen (N_2) atmosphere	Acid red 18	0.4	15 ± 1	12	6.6	150	134.17	[128]
	Ammonium chloride (NH_4Cl) PW = 700 W t = 15 min Nitrogen (N_2) atmosphere		0.4	15 ± 1	12	6.6	150	111.94	

	Phosphorus acid (H_3PO_4) PW = 700 W t = 15 min Nitrogen (N_2) atmosphere		0.4	15 ± 1	12	6.6	150	95.22	
Plantain leaf (*Musa paradisi acal* L)	Phosphorus acid (H_3PO_4) FR = 450 MHz PW = 700 W t = 10 min Inert atmosphere	Malachite green	20	27.85	1.333	8	-	266.8	[137]
Orange peel	CO_2 activation in microwave heating FR = 2450 MHz PW = 1000 W t = 15 min Flow = 5 L/min	Congo red	3	-	24	2-3	120	91	[146]
	Steam activation in microwave heating FR = 2450 MHz PW = 1000 W t = 15 min Flow = 5 L/min		3	-	24	2-3	120	136	
Banana peels	FR = 2.45 GHz PW = 1500 W t = 10 min Temp. = 500 °C Nitrogen (N_2) flow = 100 mL/min	Malachite green	0.01 g	-	2	5	150	1790.30	[136]
	FR = 2.45 GHz PW = 1500 W t = 10 min Temp. = 900 °C Nitrogen (N_2) flow = 100 mL/min		0.01 g	-	2	5	150	2297.83	
Aquaculture wastewater treatment									
Corncob	PW = 616 W t = 25 min CO_2 flow = 150 cm^3/min	Ammoniacal nitrogen	0.2 g	30	24	4	150	78.05	[147]
Palm kernel shell	PW = 700 W t = 30 min Vacuum = 8-15 kPa	Ammonia	-	-	-	-	-	180.0	[138]
		Total suspended solid	-	-	-	-	-	273.3	
Microalgal (*Spirulina sp.*)	Magnesium oxide PW = 400 W t = 10 min	Phosphate	2	-	6	6	-	8.9	[148]
		Nitrate	2	-	7	5	-	7.9	

"-" denoted as N/A, "PW" refers to power, "FR" refers to frequency, "t" refers to time, "temp." refers to temperature.

6. Challenges and future prospective

Treating wastewater using engineered biochar produced through microwave-assisted methods presents a range of complex challenges that demand careful thought and innovative solutions for successful execution [149]. These challenges span various aspects, from producing and defining the characteristics of biochar to applying and integrating it into existing treatment systems. The wide array of materials used as feedstock presents a notable hurdle in maintaining consistent biochar quality for wastewater treatment purposes [150]. Biomass feedstocks display significant diversity in their composition, including moisture, lignin, ash content, and elemental makeup, all of which profoundly affect the physical and chemical properties of the resulting biochar. This diversity complicates efforts to ensure uniformity in biochar attributes such as surface area, pore distribution, functional groups on the surface, and elemental composition, thereby affecting its ability to adsorb contaminants from wastewater. Dealing with this variability in feedstock necessitates a thorough understanding and control of factors like feedstock selection, preprocessing, and pyrolysis conditions to produce biochar with desired properties. Additionally, establishing standardized procedures for feedstock characterization and quality control is crucial to guarantee the consistency and dependability of biochar-based treatment systems [151].

Microwave-assisted pyrolysis provides a swift and energy-efficient means of producing biochar. Nevertheless, refining process parameters poses significant challenges. The intricate interaction among microwave power, heating speed, duration, feedstock composition, and reactor configuration influence the chemical conversion processes and the characteristics of the resulting biochar. Inadequate process conditions may result in fluctuations in biochar yield, porosity, surface chemistry, and capacity for adsorbing pollutants, thus impacting its effectiveness in treating wastewater. Overcoming this obstacle necessitates systematic experimentation, advanced modelling methods, and optimization algorithms to pinpoint the most effective process parameters for maximizing both the quality and performance of biochar. Additionally, integrating monitoring and control systems into the process can enhance reproducibility, efficiency, and scalability, thereby facilitating the transition of microwave-assisted pyrolysis technologies from laboratory experiments to practical applications [152].

Wastewater presents a complex mix of pollutants, including heavy metals, organic substances, pathogens, and emerging contaminants, posing significant hurdles for effective treatment. Engineered biochar, with its expansive surface area, porous structure, and functional

groups, demonstrates versatile adsorption capabilities. Nonetheless, achieving specificity and selectivity toward target pollutants remains a crucial challenge [153]. Factors like pollutant concentration, solution chemistry, pH, temperature, contact time, and competition from other ions influence the efficiency of biochar-based adsorption processes. Furthermore, the mechanisms governing pollutant adsorption, release, and movement within biochar matrices are intricate and multifaceted, involving physical, chemical, and electrostatic interactions [154]. Understanding these mechanisms is vital for optimizing biochar performance, improving pollutant removal efficiency, and reducing the risks of secondary pollution. Advanced characterization methods such as spectroscopy, microscopy, surface analysis, and theoretical modelling and simulation are essential tools for deciphering complex adsorption mechanisms and designing customized biochar materials for specific wastewater treatment needs.

Moving from laboratory-scale experiments to practical application at pilot and full-scale levels poses considerable challenges concerning scalability, cost efficiency, and integration with existing treatment infrastructure. Adapting biochar-based technologies from the lab to real-world scenarios requires careful consideration of factors such as feedstock availability, production scalability, economic viability, and treatment effectiveness. Furthermore, integrating biochar-based adsorption units into existing treatment facilities entails retrofitting and optimization to ensure compatibility, effectiveness, and dependability [3]. Tackling these scale-up challenges requires interdisciplinary collaboration among engineers, environmental scientists, policymakers, and stakeholders to devise robust and economically viable solutions for various wastewater treatment contexts. Additionally, conducting thorough techno-economic evaluations, lifecycle analyses, and risk assessments can offer insights into the environmental, social, and economic implications of expanding biochar-based wastewater treatment technologies, aiding decision-making and investment planning [155]. Regulatory frameworks and policy limitations present further obstacles to the widespread adoption and implementation of biochar-based wastewater treatment technologies. The lack of comprehensive regulatory guidelines and standards for biochar production, characterization, and application in wastewater treatment hampers the establishment of standardized protocols and best practices. Moreover, uncertainties regarding the long-term environmental impacts, health hazards, and regulatory compliance of biochar-based treatment systems may discourage investment and deployment by regulatory bodies, local governments, and industry stakeholders. Addressing these regulatory and policy challenges demands active involvement and collaboration among policymakers, regulators, researchers, industry representatives, and

community members to develop evidence-based guidelines, regulations, and incentives that promote the safe, sustainable, and responsible utilization of biochar in wastewater treatment processes.

Although engineered biochar for wastewater treatment poses significant challenges, it also opens avenues for innovation, collaboration, and progress. The potential for enhancing wastewater treatment with biochar derived from microwave-assisted methods depends on strategic interventions and collective efforts across various fronts. Progress in feedstock selection and processing techniques shows promise in overcoming variability challenges and optimizing biochar quality. Through the utilization of advanced biomass characterization methods, genetic engineering, and precision farming techniques, it becomes feasible to customize feedstock composition and quality to produce biochar with desired attributes [156]. Additionally, exploring new pretreatment methods and additives has the potential to enhance the consistency and reactivity of biochar, thus enhancing its effectiveness in wastewater treatment applications [157].

Sustained exploration and advancement in microwave-assisted pyrolysis technologies are imperative to achieve scalable and efficient biochar production. Emerging improvements in reactor design, process regulation, and microwave interaction mechanisms present opportunities to boost pyrolysis effectiveness, energy utilization, and biochar output [158]. Additionally, integrating process enhancement algorithms, machine learning methodologies, and computational simulations can expedite the identification of optimal process parameters, enhancing the reproducibility and scalability of biochar production [159]. Advancing biochar materials science and engineering is essential for tailoring biochar properties to address specific challenges in wastewater treatment. Through surface functionalization of biochar, incorporation of catalytic nanoparticles, or modification of pore structures, it becomes feasible to enhance biochar selectivity, adsorption capacity, and regeneration efficiency for targeted contaminants. Furthermore, exploring synergistic combinations of biochar with other adsorbents or treatment methods can unlock synergistic effects and achieve superior treatment outcomes for intricate wastewater compositions [160].

Embracing integrated treatment systems and circular economy strategies can amplify the sustainability and adaptability of biochar-based wastewater treatment solutions [151]. Combining biochar adsorption with biological, physical, or chemical treatment methods can achieve a holistic approach to pollutant removal, resource reclamation, and energy production.

Moreover, exploring synergies between wastewater treatment and other sectors like agriculture, energy, and materials presents opportunities to valorize by-products, reduce waste generation, and promote sustainable resource management practices [161]. Establishing supportive policy frameworks, regulatory standards, and financial incentives is crucial for expediting the uptake and implementation of biochar-based wastewater treatment technologies. Facilitating dialogue and decision-making processes involving policymakers, regulators, industry players, and community members can encourage consensus-building, knowledge dissemination, and capacity-building efforts. Additionally, investing in public awareness initiatives, technology showcases, and stakeholder training initiatives can cultivate greater acceptance, trust, and confidence in biochar-based solutions, easing their integration into mainstream wastewater treatment methodologies.

Although hurdles remain in harnessing engineered biochar from microwave-assisted methods for wastewater treatment, strategic actions and cooperative endeavours present avenues for innovation and progress. By tackling issues like feedstock diversity, refining pyrolysis techniques, understanding adsorption mechanisms, surmounting scale-up obstacles, and cultivating favourable policy landscapes, the complete capabilities of biochar-based technologies in addressing worldwide water issues can be unleashed. Embracing interdisciplinary cooperation, harnessing advanced technologies, and adopting comprehensive approaches are vital for achieving sustainable and efficient solutions in wastewater treatment utilizing engineered biochar.

7. Conclusion

The increasing concern over water pollution underscores the critical need for efficient, cost-effective pollutant removal methods. With its renewable nature, affordability, and adjustable properties, biochar emerges as a formidable solution, particularly when produced through microwave-assisted pyrolysis. Microwave-assisted pyrolysis enhances biochar's effectiveness by boosting its surface area and enriching its functional groups, which are crucial for adsorbing various water pollutants. It is essential to prioritise enhancing biochar's physical and chemical characteristics and broadening its effectiveness against diverse pollutants. Advancements in microwave-assisted pyrolysis technology and biochar activation strategies will play a pivotal role in addressing water pollution, marking a promising horizon for environmental sustainability.

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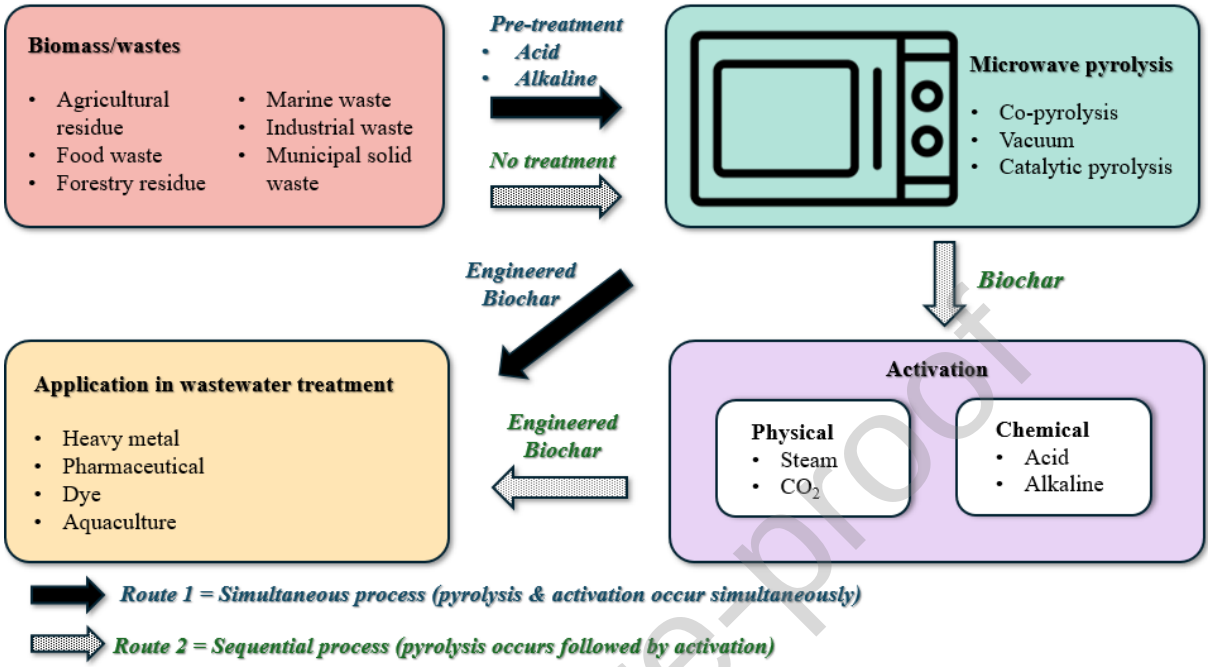
Graphical abstract



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Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐ The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Highlights:

- Engineered biochar can be an effective adsorbent for various contaminants.
- Engineered biochar possesses a BET surface area of up to 1500 m^2/g.
- Chemical activation significantly improves the porosity of engineered biochar.
- Removal efficiency in acid or alkali depends on the surface charges of biochar.