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Turning trash into tools: agricultural waste-derived biochars and composites for microplastic removal from wastewater

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Microplastics (MPs) have become ubiquitous pollutants in the aquatic ecosystem and pose a serious threat to environmental safety. The rising concerns about MP contamination have driven research into sustainable materials capable of removing MPs efficiently. Agricultural residues with the merits of low cost and high abundance can be transformed into renewable adsorbents, as burning them in open fields causes air pollution and soil degradation. Transforming agricultural wastes into biochars offers eco-friendly yet highly effective adsorbents owing to their high specific surface area, large pore volume, and chemically active functional moieties. This review offers a comprehensive evaluation of waste-derived biochars, focusing on biomass conversion routes and advanced surface modifications, including the fabrication of metal, magnetic, layered double hydroxide, mineral, and nanosize-based biochar composites, for efficient MP adsorption. Additionally, it examines the mechanisms underlying MP removal, evaluates the efficiency of biochars and composites, and integrates in-depth bibliometric and literature analyses to reveal key research trends, scientific impact, and existing knowledge gaps. This review reinforces global sustainability trends and circular economy principles by highlighting waste valorization and solutions for cleaner water and outlining future research directions and challenges to optimize the biochar efficiency and enhance its real-world performance in environmental remediation.

Sustainability spotlight

This review focuses on the sustainable transformation of agricultural biowaste into next-generation biochars engineered for efficient microplastic remediation. Repurposing biomass from open-field burning for advanced material production not only minimizes waste and CO_2 emissions but also reinforces circular economy principles and fixes environmental concerns across multiple fronts. The biochar and its advanced composites emerge as an eco-friendly, low-cost, and inherently scalable solution to conventional microplastic treatment technologies. Significantly, this work aligns with the United Nations Sustainable Development Goals (UN SDGs), including SDG 6 (Clean Water and Sanitation), SDG 12 (Responsible Consumption and Production), and SDG 14 (Life below Water), reinforcing its relevance in the pursuit of global environmental sustainability.

1 Introduction

Water is essential for human survival, as it is one of the fundamental needs. It is utilized for consumption, industrial applications, household tasks, and other purposes. The rise of unsustainable urban growth and industrial activities leads to water pollution, which includes the discharge of wastewater, hazardous effluents, and chemicals into water systems.[1] It is really concerning that about 2.6 billion people do not have basic sanitation facilities. At the same time, approximately 1.2 billion people do not have access to clean drinking water, leading to countless cases of waterborne diseases and heavy metal poisoning each year. According to the World Health Organization (WHO), one in four people globally lacks access to safe drinking water, and each year, 3.5 million people die from diseases associated with unsafe water consumption, 84% of whom are children and nearly 98% live in developing countries.[2] Water sources are increasingly contaminated by various pollutants including pesticides,[3] dyes,[4–7] pharmaceuticals,[8] heavy metals,[9–12] personal care products,[13] plastic wastes,[14] and phenolic substances.[15] Among all these, plastic pollution has become a huge environmental crisis. Shockingly, over five trillion plastic particles, adding up to over 268 000 tons, have been found in the world's oceans,[16] and projections suggest that yearly emissions could reach 53 million metric tons by 2030.[17] When plastic enters the environment, it gradually builds up and breaks down over time due to weather conditions. Hence, plastic pollution has become a major global concern that has to be addressed immediately through practical and attainable

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solutions. Reports indicate a worrying rise in MP pollution all over the world, which majorly comes from land-based sources and ultimately contaminates aquatic ecosystems.[18]

Generally, the size of MPs ranges from 1 μm to 5 mm, and they originate from multiple sources such as everyday consumer goods, industrial by-products, and the fragmentation of larger plastic materials.[19,20] They are made up of various kinds of polymers such as polystyrene (PS), polyethylene (PE), and polypropylene (PP), and they float or sink in water depending on their densities.[21] The environmental behaviour of these particles is influenced by their charge properties, which can change according to the polymer type and aquatic conditions. MPs not only pose direct physical and chemical risks to marine organisms but also act as carriers for other environmental toxins, further increasing their harmful effects.[21] Their small size allows them to penetrate biological membranes and build up within organisms, where they can possibly disrupt cellular functions. This bioaccumulation raises concerns about food security, as the ingestion of contaminated aquatic species can introduce MPs into the human body, causing long-term health effects such as oxidative stress, disruption of endocrine functions, damage to nerves, and immune system dysregulation.[22,23] The widespread occurrence of plastic pollution has been further intensified by the COVID-19 pandemic due to the increased use of plastic-based medical and personal protective equipments, contributing to the global MP crisis.[16,24] Due to their persistent nature and harmful effects, it is important to quickly adopt sustainable strategies that can reduce plastic pollution and protect both environmental safety and human health.

Various physical, chemical, and biological methods are currently being developed for the removal of MPs from aquatic environments. Techniques like filtration,[25] adsorption,[26] coagulation,[27] magnetic extraction,[28] membrane bioreactor processes,[29] biodegradation,[30] and advanced oxidation process[31] are being actively explored for their efficiency in removing MP contaminants. Although most of the above-mentioned techniques have shown promising removal rates, scaling up these techniques to large-scale applications remains a challenge due to high operational and maintenance costs. Among them, adsorption stands out as a rapid, inexpensive, and flexible

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method for water purification and reutilization. This process involves the movement of solutes from the liquid phase to the surface of a solid material, and is widely used to remove both organic and inorganic pollutants from various types of industrial wastewater. The growing need for low-cost adsorbents has driven significant research interest in recent years. In this regard, biochar, a carbonaceous solid material produced through the thermal treatment of biomass such as wood, manure, and agricultural waste, has attracted significant attention as a sustainable adsorbent for wastewater remediation.[32] The growing demand for food has led to a significant rise in global agricultural wastes, with annual production increasing from approximately 998 million tons to tens of billions of tons over the past five decades.[33] Transforming this waste into valuable products such as biochars offers an economical and environmentally sustainable solution for waste management. The biochar not only plays an important role in environmental protection but also serves as an effective solution for water purification. Its wide-ranging applications can be attributed to its desirable physicochemical properties including high surface area, porous structures, stable carbon frameworks, abundant oxygen-containing functional groups on the surface, and high ion exchange capacity. These features enhance its adsorption ability towards a broad spectrum of contaminants including inorganic ions, organic compounds, and emerging pollutants like MPs.[34] Feedstock and production conditions can significantly influence the composition and adsorption performance of the biochar produced. Surface functionalities and performance of the biochar can be further enhanced by incorporating it with various metallic, polymeric, magnetic, and nanosize-based structures.[35,36] A wide array of agricultural by-products including wood, grain hulls, bagasse, peanut shells, rice straw, corn cobs, and soybean straw have been successfully used as precursors.[36,37]

Studies have demonstrated that the biochar and its composites are highly effective in removing diverse pollutants.[38,39] However, despite the growing recognition of MPs as a major environmental threat, only a limited number of studies have focused on developing biochar-based materials specifically for their removal. This highlights the need for further research to optimize the biochar for MP remediation and expand its role in sustainable water treatment technologies. This review offers a comprehensive analysis of agricultural waste utilization, with a special focus on its application in treating wastewater through the generation and use of biochars. It explores various methods of preparing biochars from agricultural wastes, evaluates their effectiveness in removing various pollutants, and underscores the role of biochar composites in enhancing the adsorption performance. Recent advancements in MP removal *via* biochar adsorption are showcased, along with suggestions for future research to improve and expand biochar-based technologies. By transforming agricultural wastes into an effective tool for water purification, the study promotes sustainable waste utilization and environmental protection. The importance of this study lies in its connection to key United Nations Sustainable Development Goals, including SDG 6 (Clean Water and Sanitation), SDG 12 (Responsible Consumption and Production), and SDG 14 (Life Below Water), contributing to the development of eco-friendly alternatives to address global pollution challenges.

2 Bibliometric analysis

The bibliometric data were created by applying the Scopus search string using keywords "(biochar AND microplastic AND (wastewater OR water OR adsorption OR composite OR "agricultural waste" OR biomass))", meant to retrieve articles associating biochars with MPs and wastewater treatment and biomass-based materials. The initial search retrieved 287 documents, following which review articles, book chapters and non-primary sources were removed so as to focus on research output. This led to a refined dataset containing 191 publications, all the research articles and conference papers. The captured records were further analyzed by subject category, publication trend, type of document and world distribution of research by using the Scopus built-in analytics. Fig. 1 shows the subject area distribution, indicating a predominant contribution from Environmental Science (40.2%), then Chemical Engineering (11.9%), Engineering (10.8%), Chemistry (8.8%) and other subject areas, which suggested that research on biochar-based MP remediation is mainly based on environmental and chemical engineering field. The downward trend illustrates a marked increase in production from 2021, with quick rise through 2024 and a peak at 2025, indicating that global concern on MP pollution and sustainable biochar uses is escalating. The country-wise distribution reveals that China was the most productive country, followed by the United States, Australia, India, and Saudi Arabia, reflecting significant research participation from both developed and developing countries.

The processed Scopus dataset was imported into VOSviewer (v. 1.6.20) to conduct bibliometrics mapping, which allowed gaining further understanding of the relationships between keywords, research clusters, and identification of potential thematic areas within the field. Fig. 2 represents the keyword co-occurrence network based on author keywords and index keywords from the same data set showing the most relevant clusters in the research field. Bigger nodes such as MP, biochar, plastic, and soil pollution in the co-occurrence map are high-frequency keywords, which represent the key research areas. Specific research focuses are captured within colored clusters: red clusters (adsorption mechanisms, wastewater treatment, and engineered biochars), green clusters (environmental fate, soil interactions, and ecological outcomes), and blue clusters relate to composite materials, co-contamination by heavy metals and pyrolysis-related chemistry. The appearance of yellow-shaded nodes in the network represents dissolved organic matter, reaction kinetics, and magnetic biochars, which symbolize the emerging research fronts. In general, the co-occurrence map reveals a transition from the early research of adsorption and pollutant removal to advanced topics such as the development of composite biochars, interactions among multiple pollutants, and transformation of environment, which reflect an active and advancing research field.

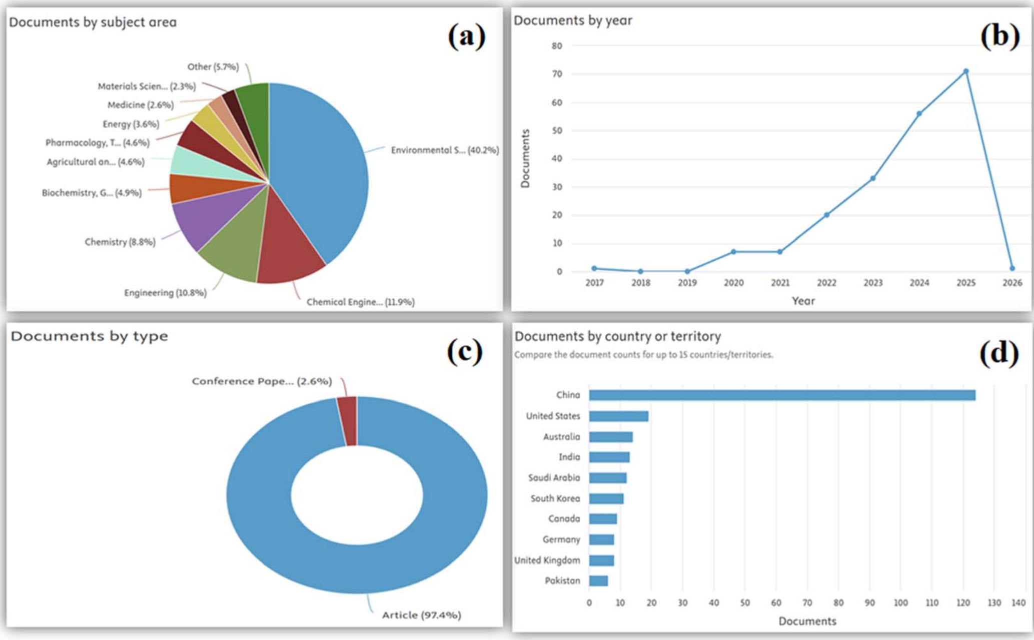


Fig. 1 Bibliometric analysis of Scopus publications on agricultural waste-based biochars for the removal of MPs. Analysis was made on the (a) distribution of documents by subject area, (b) year-wise global publication trend since 2017, (c) distribution of documents by article type, and (d) contributions to documents by country.

Fig. 3 shows the country co-occurrence network map from obtained dataset. The size of each node represents the output of publications, and the linked lines between nodes indicate the strength of research collaboration. China is the largest node, indicating its leading role in the restoration of biochar applications in MPs, followed by strong collaborative links of the United States and India. The overlay color scale indicates the age of the contributions with yellow colors representing contributions from an earlier period. Japan, Italy, Spain, Iran, and Vietnam are observed in lighter colors, representing the new players in the area in 2023–2025, while Finland, Poland, and Belarus are early contributors in this field. We also observe

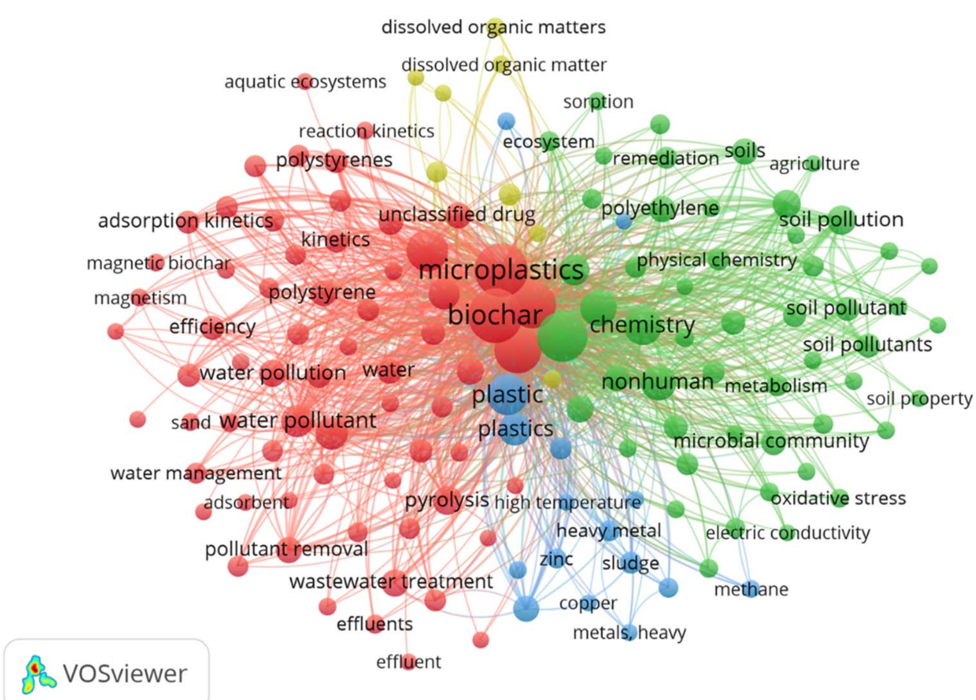


Fig. 2 Keyword co-occurrence network map using VOSviewer (based on Scopus dataset) indicating leading research clusters, thematic hot-spots, and rising trends in biochar-mediated MP remediation.

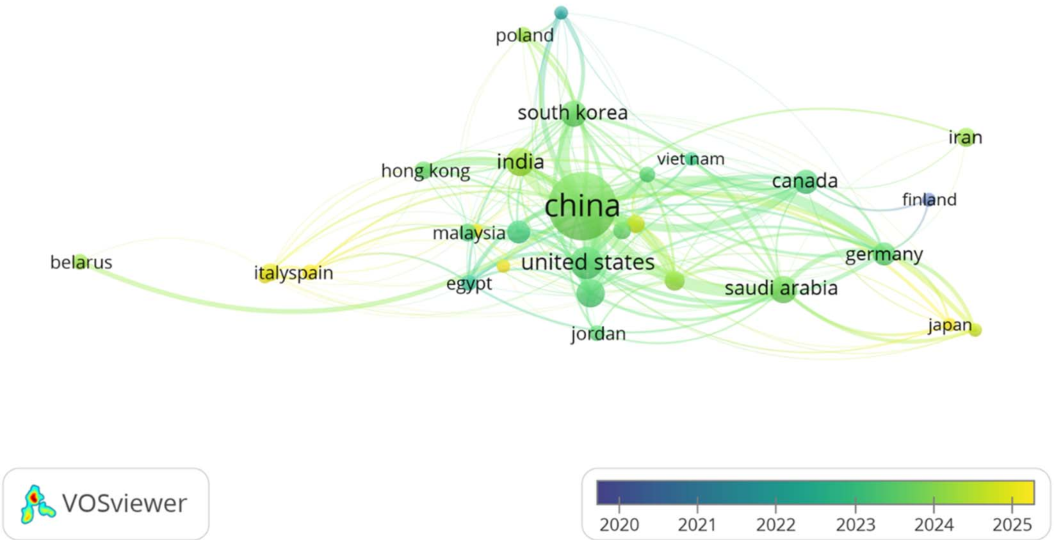


Fig. 3 Country co-occurrence network analysis on biochars from agricultural waste for MP removal obtained from the Scopus dataset and generated by VOSviewer, showing the most productive country and link strengths.

the emergence of multi-lateral relations amongst Asia, North America and Europe in the network, indicating a globalization trend in biochar-based MP remediation research.

3 Agricultural waste: literature review

Waste management is among the most urgent issues confronting humanity in this century. In 2016, global waste generation reached around 2017 million tons, and it is projected to rise to 2586 million tons by 2030 and further escalate to 3401 million tons by 2050. The primary contributors to this growing issue are the regions of Europe and Central Asia, East Asia and the Pacific, and South Asia. Fig. 4 illustrates the volume of wastes generated by different regions in the years 2016, 2030, and 2050.[33]

Agricultural waste, whether in the form of raw materials, intermediates, or final products, is generated as a by-product of various agricultural activities along the value chain. Activities and procedures like bush clearing, weeding, land preparation, consumption, harvesting, and industrial processing all contribute to the production of significant amounts of wastes. Waste

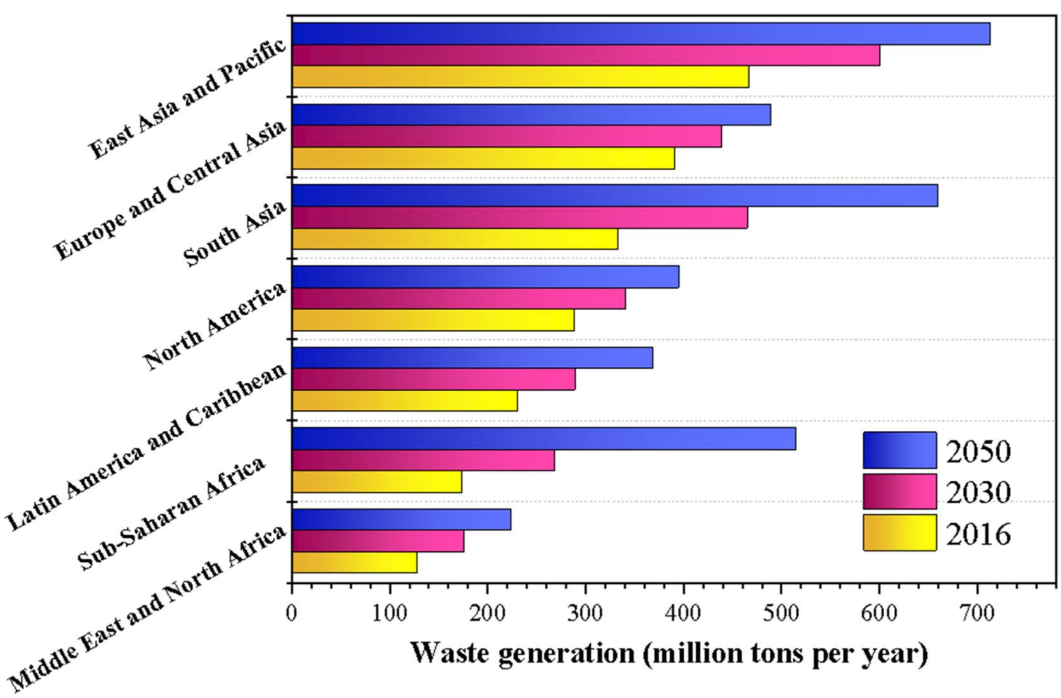


Fig. 4 Global waste generation by various regions in 2016 and projected estimates for 2030 and 2050.[33]

generation has risen alongside the growth of the agricultural sector, driven by the need to sustain socioeconomic development, supply raw materials for industries, and provide enough food to the world's continuously growing population. The global production of agricultural waste is nearly five times higher than municipal solid waste and second only to industrial waste, especially in countries with significant farming and agricultural practices.[40] The majority of this waste is biodegradable and does not significantly harm the environment, but when it accumulates and is present in large enough quantities, it can have negative environmental effects. In Asian nations, crop residue burning is a serious issue that requires robust technological solutions and legislative backing. Nearly 25% of the world's agricultural biomass is burned in open fields every year. The burning process releases greenhouse gases into the atmosphere and introduces dangerous substances into the soil and water.[41] The food system including agriculture and land use, storage, transport, packaging, processing, retail and consumption, is responsible for 21–37% of total greenhouse gas emissions.[42] Improper disposal and handling of waste biomass pose significant social, health, and environmental problems. Burning, clearing drains, and using dump sites are examples of inappropriate and unsustainable agricultural waste management that cause bushfires, worsen deforestation, release odours, and serve as breeding grounds for harmful pathogens, rodents, cockroaches, mosquitoes, and flies.[43] These negative consequences can significantly affect human health and the environment.

4 Agricultural waste valorization

Unlike conventional and linear agriculture practices, the agricultural sector embraces circular economy, promotes waste valorisation, and provides cost-effective solutions for environmental sustainability. Agricultural waste, when properly managed, can be converted into a diverse array of valuable products including bioenergy, bioplastics, animal feed, building materials, and bio-based chemicals. These viable approaches not only minimize ecological liabilities but also offer economic benefit to the agricultural industry.[44] Fig. 5 represents the various valorisation routes of agricultural waste, ranging from conventional methods to sustainable approaches.[44–47] The subsequent sections will address the advancement of agricultural waste in different fields.

4.1 Energy production

Agricultural waste is a sustainable source of bioenergy that offers a viable substitute to fossil fuels. Agricultural waste, which is primarily composed of cellulose, hemicellulose, and lignin in ratios of 4 : 3 : 3, has a higher energy conversion efficiency than fossil fuel-based energy generation technologies.[48] Anaerobic digestion is generally used to generate biogas (primarily methane) from waste biomass. This biogas can be utilized to produce heat and generate electricity.[49] Frankowski and co-workers found that the biogas efficiency for certain waste biomass is quite high. It is around 208.8 m^3 Mg^{-1} of fresh mass for hemp straw and 165.62 m^3 Mg^{-1} of fresh mass for steamed potato peel.[49] According to the studies, establishing a biogas plant can reduce carbon emissions as much as 6.78 tons of CO_2/village/day. Moreover, biogas is considered a low-carbon fuel source with emissions ranging from 50 to 450 gCO_2eq kWh^{-1}.[50] Agricultural waste can also be used to generate bio-oil and biofuels. By 2050, up to 27% of the world's transportation fuel may be replaced by biofuels made from biomass, potentially reducing greenhouse gas emissions.[51] The

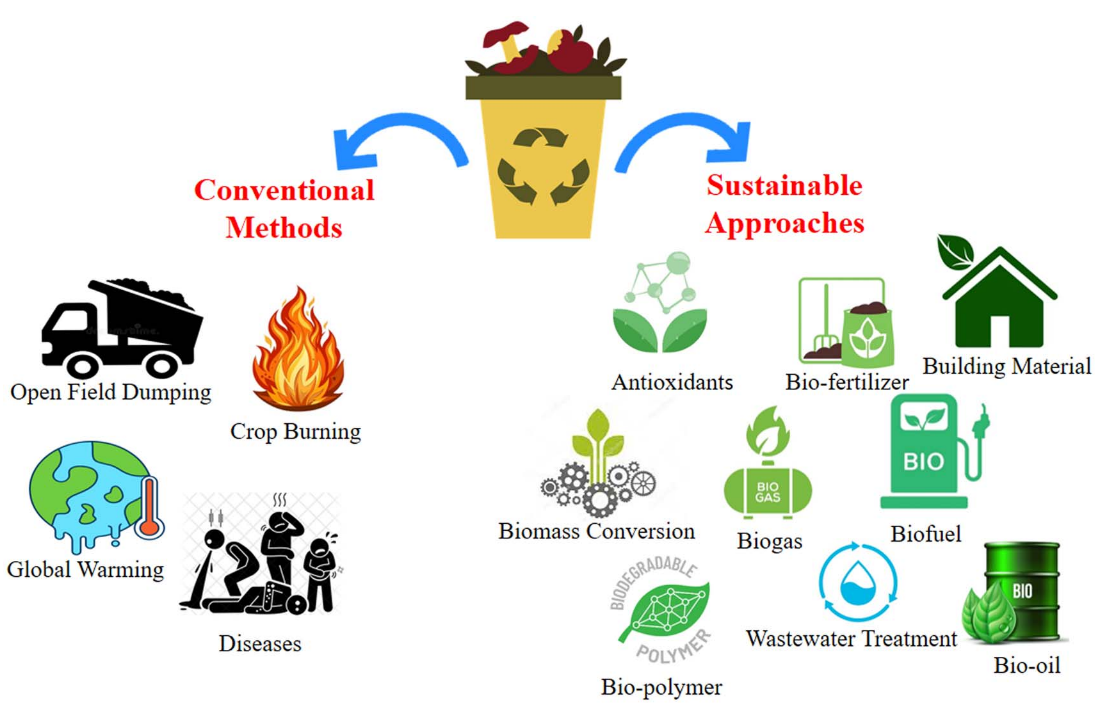


Fig. 5 Valorization routes of agricultural waste, ranging from conventional methods to sustainable approaches.

agricultural waste that is rich in carbohydrates such as sugarcane, coconut shells, fruit peels, oil palm residues, rice husks, maize, and vegetables serves as an ideal feedstock for biofuel production. This waste debris can produce advanced biofuels like bioethanol and biodiesel, which can be mixed with gasoline for transportation and used as an alternative to diesel. These waste residues are also used in CHP (Combined Heat and Power) systems for the generation of heat and electricity.[52]

4.2 Biodegradable products

Agricultural waste materials such as rice husks, corn starch, and sugarcane bagasse can be turned into biodegradable plastics or biocomposites. Compared to plastics made from fossil fuels, bioplastics are less harmful, biodegradable, and renewable resources, and have a smaller carbon footprint. The fabrication of biopolymers with desirable properties, such as synthetic plastic materials like polybutylene (PB), polyhydroxyalkanoates (PHA), polybutylene succinate (PBS), polyglycolide (PGA), and poly-lactic acid (PLA), has been made possible by advanced biotechnology processes. Biocomposites, also known as agricultural waste-based composites, are created by utilizing natural agricultural residues as a matrix, reinforcement, or both. Recently, there has been a growing attention in developing novel eco-composites that capitalize on the sustainable qualities of bio composites while allowing the alteration of physical characteristics. The biocomposites are significantly utilized for non-structural and non-load-bearing purposes. Natural fibre-reinforced biocomposites are widely utilized in household goods, packaging materials, and automobiles due to their ultralight structure.[53] For instance, in a research study, Arpitha *et al.*[54] used boron nitride particles and corncob waste for the fabrication of an epoxy-based composite with the goal of enhancing the composite's strength for real-world uses while also providing an economical, environmentally friendly waste disposal solution. Furthermore, Baseri reported improved UV protection efficiency of wool yarn using bio-mordants from gallnuts and banana shells, which enhanced UV protection by up to 59.79% and 25.33%, respectively.[55]

4.3 Pharmaceuticals and biochemicals

A valuable and innovative method for producing high-value products like antibiotics, bioactives, antioxidants, chemicals, nutraceuticals, biopeptides, biopolymers, essential industrial enzymes, polyphenols, polysaccharides, lipids, bio-nanocomposites, minerals, pigments, vitamins, and fatty acids is the valorization of agricultural wastes. These elements can be extracted from waste materials and used as a possible substrate for a number of applications in industries such as cosmetics, environmental initiatives, agriculture, health, food, and pharmaceuticals.[56] The methods and circumstances of extraction affect the overall composition and characteristics of the bioactive substances. Waste biomass contains a variety of compounds including alkaloids, phenolics, polyphenols, tannins, carotenoids, peptides, anthocyanins, terpenes, flavanols, essential oils, flavonoids, fatty acids, dietary fibres, enzymes, nitrogenous compounds, minerals, lipids, amino acids, carbohydrates, chemicals, vitamins, and other phytoconstituents required for the fabrication of biochemicals. The presence of these bioactive compounds reduces the risk of Alzheimer's disease, heart-related diseases, aging-related disorders, cataracts, and certain cancers. Furthermore, their antioxidant qualities, antimicrobial effects, ability to prevent food deterioration, use as dietary supplements, and therapeutic applications make them highly valuable in pharmaceuticals.[57]

4.4 Building materials

Waste biomass can be effectively used to produce sustainable building materials. In the manufacturing of cement blocks, agricultural wastes like coconut shells, peanut shells, rice straws, and rice husks have partially replaced sand. Moreover, the fibres from barley and wheat straw improve soil composition for brick formation with enhanced properties suitable for safe and eco-friendly building materials. Additionally, studies have shown that using straw bales rather than soil creates more ecologically friendly structures. This problem has been attributed to materials with low embodied energy and favourable thermal performance. In addition, building materials derived from agricultural wastes have been shown to be viable alternatives to achieve sustainability goals while lowering pollution and other negative effects.[58] Natural lignocellulosic fibre derived from agricultural wastes such as date palm, sunflower, flax, and hemp has already been investigated and used as an insulating material. Research indicates that when it comes to low-density insulation materials, the density of the panels tends to have a major impact on thermal conductivity.[58]

4.5 Wastewater treatment

The benefits of using agricultural wastes in the production of adsorbents include their abundance, affordability, and environmental friendliness. Due to the abundance of surface functional groups and lignocellulosic and carbonaceous nature, agricultural wastes can be used as substitutes for commercial activated carbon.[44] Rice husks, orange peels, fruit shells, banana fronds, tamarind seeds, cottonseed hulls, avocado peels, and many other waste materials have been used to make a variety of adsorbents. The lignocellulosic materials found in agricultural wastes are primarily made up of cellulose, hemicellulose, lignin, and numerous other functional groups that can remove various wastewater pollutants.[44] The porous structure with high specific surface area of agricultural waste-derived materials, such as activated carbon and biochar help, lower pollution levels by trapping toxic pollutants. Additionally, these materials help mitigate the harmful effects of global warming by capturing CO_2.[44,59,60] This waste is also used to make biochar, a superior adsorbent. For instance, research by Ahmed *et al.*[61] reported the utilization of magnetized orange peel waste for the adsorption of crystal violet dye, with an equilibrium adsorption capacity of 46.94 mg g^{-1}.

4.6 Other applications

Agricultural by-products offer several other valuable uses. For instance, crop residues such as those from corn, wheat, and rice, along with by-products of fruit and vegetables, can be processed into animal feed.[62] Additionally, numerous studies have explored the use of materials like coir fiber, coffee husk ash, wheat straw, and corn husk fiber to enhance the properties of expensive soils. These studies found that such treatment helps reduce crack formation and improve factors such as soil shrinkage, unconfined compressive strength (UCS), and California Bearing Ratio (CBR).[63] Research studies also demonstrated the potential of using metal oxide/biochar composites obtained from agricultural wastes for the development of sustainable high-energy supercapacitors.[64] In addition, the nutrient-rich nature of waste biomass makes it a valuable resource for biofertilizer production, providing a green alternative for improving soil quality, promoting crop production, and minimizing the need for chemical fertilizers. The production of organic fertilizer demonstrates a sustainability index of 74.55%.[65] Collectively, the valorisation of waste biomass aids in pollution control, carbon emission reduction, resource conservation, and reinforcement of sustainable practices. Among the various valorisation techniques outlined, the conversion of waste biomass into biochars has received more attention due to their simplicity, durability, and high relevance to water treatment applications.

5 Agricultural waste-derived biochars

Biochar is mainly composed of carbon, hydrogen, oxygen, nitrogen and ash along with various minerals such as sodium, potassium, and calcium. It is characterized by a high surface area and a well-developed pore size that includes micropores (up to 2 nm), mesopores (2–50 nm), and macropores (larger than 50 nm). The specific properties and composition of the biochar can vary significantly depending on the raw material used and the conditions under which it is produced. Biochars can be classified into a wide variety of types based on the origin of the feedstock, such as sludge-derived biochars, manure-derived biochars, and lignocellulosic biochars (obtained from wood, straw, husks, and shells).[66] Among them, lignocellulosic biomass is commonly recognized as a better precursor due to its high organic carbon content and low ash proportion, which promote the creation of stable, aromatic carbon frameworks during thermal processing. Consequently, agricultural biowaste

Table 1 Waste biomass-derived biochars: feedstock sources, preparation methods, target pollutants removed, and corresponding adsorption capacities

S. No.	Waste biomass used (feedstock source)	Preparation method	Pollutant removed	Adsorption capacity (mg g^{-1})	Ref.
1	Groundnut shell	Slow pyrolysis	Basic blue 41	22.322	72
2	Rice straw	Pyrolysis	Cd(II)	64.4	73
3	Mugwort stem	Pyrolysis	Cr(VI)	161.92	74
			Cu(II)	155.96	
4	Corn stalk	Pyrolysis	Pb(II)	21.6	75
5	Jackfruit peel	Hydrothermal carbonization	Pb(II)	83.86	76
6	Potato peel	Pyrolysis	Cd(II)	33.76	77
7	Switch grass	Pyrolysis	Methylene blue	196.1	78
8	Olive mill	Hydrothermal carbonization	Iodine	1203	79
			Methylene blue	617	
9	Oil palm frond	Steam pyrolysis	Phenol	62.89	80
			Tannic acid	67.41	
10	Grape pomace	Pyrolysis carbonization	Cymoxanil	161.0	81
11	Sugarcane	Slow pyrolysis	Thiamethoxam	10.17	82
12	Bamboo	Hydrothermal pyrolysis	U(VI)	274.15	83
13	Lotus root	Carbonization pyrolysis	Methyl orange	320.0	84
14	Corn stalk	Pyrolysis	Cd(II)	33.81	85
			As(III)	148.5	
15	Wheat straw, softwood	Pyrolysis	Caffeine	22.8	86
			Chloramphenicol	11.3	
			Bisphenol A	31.6	
16	Wood waste	Gasification	Ibuprofen	39.9	87
17	Coconut shell	Pyrolysis	Diazinon	9.65	88
18	Rice husk	Pyrolysis	Basic violet 03	12.64	89
19	Sugarcane bagasse	Slow pyrolysis	Methylene blue	30.13	90
20	Food-plant trimmings	Heat pipe pyrolysis reactor	Tetracycline	9.45	91
21	Banana peel	Pyrolysis	Acetaminophen	57.3	92
			Ciprofloxacin	20.42	
22	Orange peel	Pyrolysis	Pb(II)	30.12	93
			Cu(II)	28.06	
23	Pistachio shell	Pyrolysis	Congo red	614.7	94
			Methylene blue	384.2	
24	Tapioca peel	Pyrolysis	Malachite green	30.18	95
			Rhodamine B	33.10	

rich in cellulose, hemicellulose, and lignin serves as an excellent and sustainable source of high-quality biochars with well-developed aromatic carbon structures and increased fixed carbon fractions.[67] In contrast, non-lignocellulosic precursors are frequently found in biochar with enhanced inorganic or ash components due to their mineral-rich composition. Compared to other carbon nanomaterials, such as activated carbon, carbon nanotubes (CNTs), carbon aerogels, and graphene, biochar has numerous distinct benefits, including cheap production costs, renewable and plentiful feedstocks, environmental sustainability, and ease of scaling applications.[66,67]

The practical implementation of biochar technology indicated that the valorization of agricultural biowaste is progressively advancing beyond laboratory-scale research. For instance, the Indian social impact startup "Takachar" has created small-scale, portable biomass reactors capable of turning crop residues into biochars and biocoal at the point of generation, effectively lowering open field burning and establishing a sustainable rural market for carbon-rich goods.[68] Table 1 summarizes the waste-derived biomass feedstocks used for biochar preparation, the corresponding preparation methods, the target pollutants removed, and the associated adsorption capacities. The selection of biomass influences the porosity and surface area of biochars. Oxygen-functional groups (OFGs), sp^2 hybridized carbon, heteroatoms (*i.e.*, N, P, S, and B), and PFRs are the primary active sites of biochars. Biochars' high specific surface area (SSA) and significant porosity allow them to accommodate these active sites for environmental applications. Reactive oxygen species (ROS) are generated during the catalytic reaction of biochar, which can be mediated by electron-rich oxygen functional groups like the ketonic (C=O) group.[69] The sp^2-hybridized carbon of biochar can supply electron-rich sites for adsorption and catalysis. Foreign elements like heteroatoms, especially S, N, B, and P, can be incorporated into the carbon structure of biochar to give it functional active sites. The knowledge of the structural characteristics of carbon in the biochar is crucial for its efficient use in environmental applications because carbon atoms make up the majority of the material, with a carbon content of over 65% of its composition. The degree of graphitization measures the similarity index between graphenes and the biochar, which is essential because a graphite-like structure enables donor–acceptor π–π electron interactions with organics.[70] Additionally, the biochar's high electrical conductivity and improved electron transfer ability within the carbon framework result in extensive conjugation of sp^2-hybridized carbons.[70] The co-existence of sp^2/sp^3 hybridization can positively affect the biochar's activity by encouraging internal electron flow (from the sp^3 donor carbon to the sp^2 acceptor carbon) and an external migration of electrons from the later carbon configuration to the oxidants.[70,71] In the graphitized structure, each carbon atom is covalently bound to three neighbouring carbon atoms by three electrons, forming layers of carbon. The fourth valence electron involved in π-bond formation is delocalized and free to travel throughout the carbon structure due to its half-filled orbital.[70] These structural features attributed to the biochar's distinctive characteristics, like its high specific surface area, hydrophobic nature, ease of functionalization, porous nature, and high carbon content, contribute to its superior adsorption capabilities.

5.1 Methods for the conversion of waste biomass into biochar

The utilization of waste-derived biochars has become more popular due to the wide range of applications across different fields (Fig. 6). Raw materials are collected and then subjected to various thermal decomposition conditions in order to produce biochars. Based on variables like temperature range, conditions, and residence time, different techniques are used for the transformation of the raw material into biochars. These techniques include gasification,[96–98] torrefaction,[99–101] hydrothermal carbonization,[102–105] and pyrolysis.[106–113] Table 2 describes the advantages and limitations associated with these methods. These techniques produce biochar (solid), bio-oil (liquid), and biogas (gaseous) in different proportions.[114] The following sections describe the processes used in biochar production.

5.1.1 Pyrolysis. Pyrolysis is a key thermal technique used to convert organic waste into materials rich in carbon, and can be used to treat wastewater. This method enriches the starting material's carbon content by thermally breaking down cellulose, hemicellulose, lignin, and fat in an oxygen-free environment. Consequently, there is an increase in the carbon content of the material. Pyrolysis process, such as carbonization temperature, heating rate, and nitrogen supply, plays a major role in evaluating the yield and quality of the synthesized carbonaceous materials.[109,110] The release of volatile compounds and gases during the heating process enhances the structural properties of biochars by reducing the oxygen-to-carbon and hydrogen-to-carbon ratios and increasing aromatic and carbon-rich nature. Based on conditions such as heating rate, time, pressure, and operating temperature, pyrolysis can be grouped as slow, fast, and microwave-assisted. The biochar formed at high pyrolysis temperatures above 773 K tends to show a larger pore volume, increased surface area, and stronger hydrophobic characteristics, resulting in excellent adsorption capacity for organic pollutants, whereas if pyrolysis occurs at temperatures below 773 K, it produces biochars with abundant oxygen-containing functional moieties and reduced pore volume and surface area for the adsorption of inorganic pollutants.[110,111]

In microwave-assisted pyrolysis (MAP), a long residence time is required due to the poor heat conductivity of biowaste. Despite conventional heaters, MAP employs microwave heating directly throughout the material to achieve rapid and uniform heating with lower energy consumption. MAP-assisted synthesis of biochars displays a higher porosity, more aromatic structures and improved surface functionalities and contributes to strong adsorption capacity.[112] Due to selective heating and faster processing, MAP is also considered a greener and eco-friendly approach. However, since most studies are limited to lab-scale batches (<50 g), pilot scale emphasizes the role of optimizing the power input and heat distribution for large-scale operations. Moreover, challenges including the dependence of microwave adsorbing additives for low dielectric biomass and technical constraints of scaling up still remain.[113]

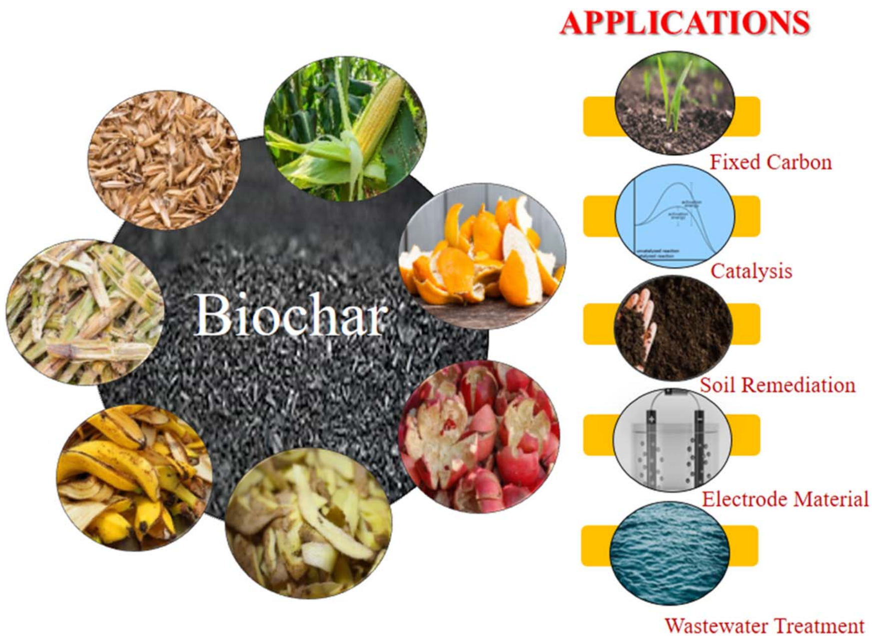


Fig. 6 Agricultural waste-derived biochars and their applications in various fields.

Table 2 Advantages and disadvantages of various methods used for the preparation of biochars

Methods	Advantages	Disadvantages
Slow pyrolysis	Good yield Relatively simple setup	Low heating rate Longer residence time Energy intensive for large batches
Fast pyrolysis	Fast heating Maximise liquid and bio-oil production Improved heat transfer	Lower biochar yield Requires precise control More complex equipment
Microwave assisted pyrolysis	Rapid and uniform volumetric heating Low energy consumption Produced highly porous biochar Better process control	Requires microwave absorbers for low dielectric feedstock Higher investment costs Scale-up limitations
Torrefaction	Mild thermal treatment Low energy input Improve biomass stability	Produces limited porous biochar Lower adsorption capability
Hydrothermal carbonization	Suitable for wet biomass No need for extensive drying	High pressure required Limited porosity Energy demand for pressurization
Gasification	Produces high energy syngas Efficient for energy recovery	Biochar is co-product Complex reactor design High operating temperature

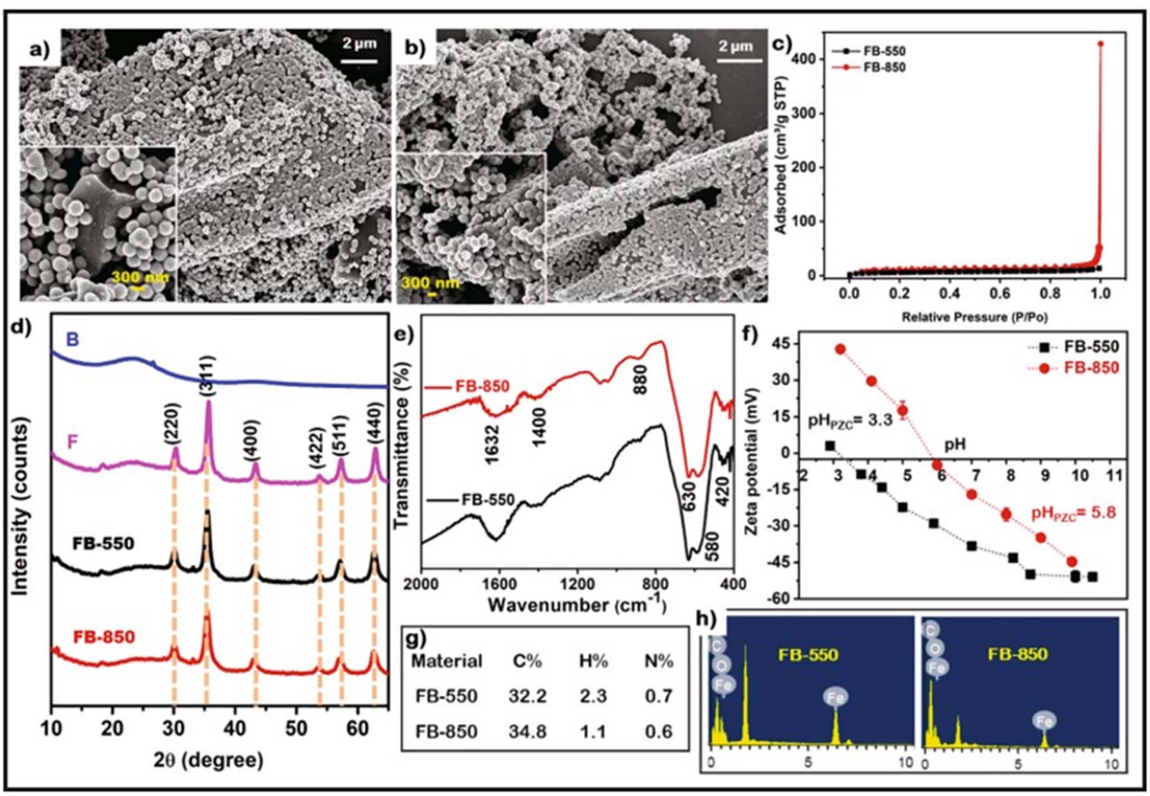
5.1.2 Hydrothermal carbonization. A very attractive thermochemical conversion technique, especially for fabricating materials with high energy densities, is hydrothermal carbonization. This method effectively converts biomass into a high-yield carbonaceous material at low operating temperatures, making it ideal for wet feedstock and limiting the necessity for energy-intensive drying procedures. Biomass is treated with a liquid at low temperatures (<473 K) under autogenous pressure in a closed chamber for several hours during the hydrothermal carbonization process.[103] This process frequently results in a drop in pH, which is explained by the production of different organic acids such as lactic, formic, levulinic, and acetic acids, that enable acid-catalysed reactions of organic compounds without the need for additional acid. Water is a solvent and a reaction medium that speeds up the hydrolysis of lignocellulosic biomass. Therefore, its presence during this process speeds up the carbonization process. Three phases are produced by the hydrothermal carbonization of biomass, which follow different mechanistic pathways. These are hydrochar (solid fraction), an aqueous phase made up of a mixture of water and bio-oil, and a small amount of gas (mainly CO_2). Research shows that compared to biochars made from pyrolysis, hydrochar made by hydrothermal carbonization is more effective at adsorbing metal ions. It is thought to be a promising technique for turning biomass into materials with a porous structure and lots of oxygen-containing functional groups, which is useful for adsorbing contaminants from wastewater.[103,104] Hossain *et al.*[105] produced rice husk biochar at 453 K through hydrothermal carbonization, which improved the biochar's surface area and porosity and increased its zeta potential, demonstrating its ability to adsorb wastewater.

5.1.3 Gasification. Through the thermochemical process of gasification, biomass or other organic materials are converted into "syngas" (85%), a gas mixture primarily composed of H_2, CO, and CO_2 with potentially trace amounts of hydrocarbons like CH_4, as well as a solid biochar (10%) and a liquid byproduct known as "tar" (5%). Char and tar are unwanted byproducts of the gasification process. At a temperature of about 973 K, the biochar was created in an oxidizing environment using either a single gas or a combination of gases.[115] Drying, pyrolysis, partial oxidation, and reduction are the four sequential steps that typically make up the gasification process. Depending on variables like the type of gasification temperature, feedstock, gasifying agent, and reactor design, the properties of the biochar produced by biomass gasification can differ greatly.[115] The characteristics of the biochar produced by biomass gasification have not been as thoroughly investigated as those of the biochar produced by pyrolysis, which has been the subject of much research. However, given its potential uses in the decontamination of water and wastewater, a thorough understanding of the properties of char and how it relates to gasification technology is crucial.[97,98,115]

5.1.4 Torrefaction. Torrefaction is a conventional thermal process used to enhance the physicochemical and thermochemical properties of biomass, primarily by increasing its energy density and biomass homogeneity. Torrefaction is typically carried out at slow heating rates under atmospheric pressure, with temperatures between 473 K and 573 K, and either with or without limited oxygen.[116] While torrefaction is primarily employed for the production of solid biofuels, pyrolysis remains the preferred method for generating biochars intended for water and wastewater treatment applications. Due to the significantly lower temperatures used during the thermal technique, torrefaction char usually has a higher concentration of oxygen-containing functional groups than biochars.[100] According to research by Pathomrotsakun *et al.*[101] the biochar produced by torrefying coffee leftovers gives an energy yield of 48.04% with a higher heating value of 31.12 MJ kg^{-1}, highlighting its potential as an efficient biofuel source.

5.2 Biochar-based composites

Various studies have been carried out to fabricate novel biochar-based composites by incorporating various materials into the biochar to address the limitations of the unmodified biochar. These new composite materials show improved physicochemical properties, including increased porosity, higher specific surface area, improved reusability, more active surface sites,



Material	C%	H%	N%
FB-550	32.2	2.3	0.7
FB-850	34.8	1.1	0.6

Fig. 7 Iron-modified magnetic biochars (FB), SEM images at (a) 550 °C and (b) 850 °C, (c) gas sorption isotherm for BET analysis, (d) XRD patterns, (e) FTIR spectra, (f) zeta potential *vs.* pH, (g) CHN elemental analysis, and (h) EDX spectrum. Reproduced with permission from ref. 117, Copyright 2021, Elsevier.

Table 3 Summary of biochar-based composites, the target pollutants removed, and their corresponding adsorption capacities

S. No.	Biochar-based composites	Pollutant removed	Adsorption capacity (mg g^{-1})	Ref.
1	Biochar fibril/MgO	Pb(II)	3410.1	124
2	Biochar/Fe_2O_3	Cr(VI)	24.37	125
		Phenol	39.32	
3	Orange peel biochar–$CaCO_3$/ZnO	Phosphate	52.96	126
4	Banana peel biochar–Fe_3O_4/ZIF-67	Cd(II)	50.78	127
5	Rice straw biochar–TiO_2	Ciprofloxacin	747.64	128
6	Fe_3O_4@SiO_2/TiO_2/g-C_3N_4	Tetracycline	147.96	129
7	Wood biochar@Cu_2O/Ag-3	Congo red	264.55	130
8	Mg/Mn–biochar	Cd(II)	316	131
9	FeAl/LDH–biochar	Cr(VI)	42.78	132
10	Drumstick biochar/Mg/Fe–LDH	Naphthol green	53	133
11	Biochar/Mg/Al–LDH	U(VI)	388.81	134
12	Pine sawdust biochar/Mg/Al–LDH	Sunset yellow FCF	23.6	135
13	Rice husk biochar/Zn/Mg/Al–LDH	Cu(II)	117	136
		Pb(II)	124	
14	Walnut shell biochar/NiCr–LDH	Methyl orange	108.2	137
15	Lychee peel biochar/Ca/Cr–LDH	Congo red	631.1	138
16	Biochar/La–MgAl–LDH	Phosphate	249.3	139
17	Hydrochar/MgAl–LDH	Congo red	348.78	140
		Methylene blue	256.54	
		Pb(II)	33.55	
18	PW_{12}(polyoxometalate)/Fe_3O_4/biochar	Metronidazole	78.45	141
19	Rice husk biochar/Ni@Na–TiO_2	Pb(II)	122.3	142
20	ZnO/biochar	Methylene blue	826.44	143
21	Lychee peel biochar/$CaFe_2O_4$	Nitrate	60.3	144
		Phosphate	57.4	
22	Y_2O_3@biochar	Oxytetracycline	223.46	145
23	Biochar/clay mineral	Methyl violet	159.02	146
24	Bentonite clay@biochar@Fe_3O_4	Hg(II)	66.66	147
25	$ZnFe_2O_4$/α-Fe_2O_3/biochar	Direct red 79	676.8	148

and improved stability, when compared to primary (*i.e.*, unmodified) biochars. Singh *et al.*[117] investigated the mitigation of MPs in aquatic environments using the iron-modified biochar pyrolyzed at two temperatures, FB-550 (550 °C) and FB-850 (850 °C), with magnetic properties for easy removal. The composites effectively removed NPs of varying sizes and surface functionalities within 10 minutes. FB-850 demonstrated superior adsorption capacities for NP1 (225.11 mg g^{-1}) and NP3 (206.46 mg g^{-1}), while FB-550 excelled for NP2 (290.20 mg g^{-1}) (Fig. 7).[117] Diverse composites can be created by varying the synthesis techniques or by modifying the ratio and composition of the carbon matrix and nanomaterials.[118] Biochar-metal composites, biochar–mineral composites, biochar–layered double hydroxide (LDH) composites, and biochar–nanocomposites are the four main types of biochar-based composites. Biochar composites have demonstrated superior performance in a range of environmental applications when compared to the unmodified biochar. Table 3 summarizes biochar-based composites, the target pollutants removed, and their corresponding adsorption capacities.

5.2.1 Biochar–metal and metal compound composites. Biochar–metal composites are created by integrating metals or metal compounds with biochars to form a material with superior functional properties. Among these, iron-based composites including iron oxide–biochars, iron sulfide–biochars, and nano zero-valent iron–biochars have received the most research attention. Numerous studies have extensively explored their synthesis methods, advanced mechanisms, and environmental applications. Overall, iron–biochar composites have demonstrated effectiveness in adsorbing and immobilizing organic contaminants and heavy metals, primarily through enhanced electrostatic attraction, surface complexation, and precipitation processes.[144] Zhang *et al.*[145] modified banana peel-derived biochar as a biochar/iron oxide composite and observed that the adsorption capacity for methylene blue improved to 862 mg g^{-1} at pH 6.1 and temperature 313 K. Apart from iron–biochar composites, various other types of metal–biochar composites such as magnesium oxide, manganese oxide, calcium oxide, potassium permanganate, zinc oxide, and titanium oxide composites are also promising options in environmental applications. There are two equally common approaches to prepare metal oxide–biochar composites: (i) pretreatment, which involves the introduction of metal oxide or its precursor to biochar feedstock prior to pyrolysis; and (ii) post-treatment, which involves the addition of metal oxide or its precursor after the feedstock has been pyrolyzed into biochar.[146]

5.2.2 Mineral–biochar composites. Composites of biochars and minerals such as silica, calcium carbonate, bentonite, kaolinite, and montmorillonite are referred to as mineral-based biochar composites. These composites benefit from the inherent properties of clay minerals, particularly their high cation exchange capacity (CEC), which is attributed to permanent negative charges resulting from the isomorphic substitution of lower valent metal ions within their tetrahedral and octahedral layers. The negative surface charges are balanced by exchangeable cations in the interlayer space, which can readily interact with various contaminants. This allows mineral biochar composites to effectively remove organic pollutants such as dyes and inorganic pollutants including ammonium (NH_4^+) and heavy metals through the cation exchange process. The integration of natural minerals not only enhances the contaminant removal capabilities of biochars but also improves soil remediation outcomes by increasing nutrient retention and soil fertility.[147]

5.2.3 Layered double hydroxide (LDH)–biochar composites. Layered double hydroxides (LDHs) are a type of anionic clay mineral made up of layers of positively charged metal hydroxides and anions in the interlayer space to neutralize charges. The general form of layered double hydroxides has the formula $[M_{1-x}{}^{2+}M_x{}^{3+}(OH)_2]^{x+}\cdot[A_{x/n}{}^{n-}.mH_2O]$, where M^{2+} and M^{3+} are the divalent and trivalent metal ions, respectively. X is the molar ratio of trivalent cations and A^{n-} is the anion within the interlayer. The physicochemical properties of the resulting biochar–LDH composites, including surface functional groups, specific surface area, structure variability, adsorption properties, and stability, showed a notable improvement due to the synergistic effect of LDH and biochars. The primary purpose of these composites is to eliminate dyes, heavy metals, anions, and antibiotics.[148] Higher selectivity and adsorption affinity for phosphate were exhibited by the biochar/MgAl–LDH combination. The maximum monolayer adsorption efficiency for phosphate and nitrate was 177.97 mg g^{-1} and 28.06 mg g^{-1}, respectively.[149]

5.2.4 Biochar–nanocomposites. The aim of developing a biochar-based nanocomposite is to synthesize an innovative material that synergistically combines the biochar with nanomaterial performance rather than just improving the biochar's inherent properties. These biochar–nanoparticle (NP) composites can be broadly divided into three groups: magnetic biochar composites, functional nanoparticle–coated biochars, and nano-metallic–biochar composites. A variety of nanomaterials including magnetic iron oxide, metallic nanoparticles, and functional nanoparticles (such as chitosan, carbon nanotubes, graphene/graphene oxide, graphitic C_3N_4, layered double hydroxides, zinc sulfide nanocrystals, and nanorange zero-valent iron) are used to functionalize the biochar. These biochar-based materials possess exceptional sorption capabilities due to their large microporosity, vast surface area, natural abundance, and unique structural qualities, enabling them to adsorb various pollutants such as minerals, vitamins, and medications from aqueous environments.[150]

6 Application of biochar and biochar-based composites in wastewater remediation for MP removal

Biochars have been extensively utilized in the fields of waste management and the remediation of toxins from soil and water due to its distinctive properties. The surface characteristics of biochar can be altered to improve the removal efficiency. The characteristics of biochar, deashing procedure, pH, adsorbent dosage, competitive anions, and temperature all influence the efficiency of pollutant removal by biochar.[151] The mechanisms for the elimination of pollutants are determined by the chemical properties of the pollutants and the biochar surface, respectively. Various research studies have shown that the biochar can be altered to enhance its properties and expand its uses in different fields. For example, Ahmed *et al.*[152] successfully synthesized rice straw-derived biochar and modified hydroxyapatite biochar nanocomposites. They found that the maximum adsorption capacity for U(VI) increased significantly from 101.78 mg g^{-1} to 423.04 mg g^{-1} in the modified biochar. This highlights the importance of exploring biochars and their composites for wastewater remediation, removing a wide range of pollutants, including heavy metals, pesticides, herbicides, dyes, MPs, and other contaminants. Among these pollutants, MPs are particularly alarming due to the difficulties associated with their removal and the limited research conducted on their eradication from water.

6.1 Removal of MPs

Plastics are ubiquitous and associated with many human endeavors; their use is increasing alongside population expansion and increased consumption. Over 360 million tons of plastics were produced worldwide in 2018, and by 2050, that amount is predicted to triple. According to a report, China is responsible for 32% of the plastic pollution, and Asia remains the leading region in both the production and consumption of plastic products.[153] In addition to secondary sources like weathering, friction, abrasion, and the decomposition of larger plastic debris, primary sources of MPs include microfibers, microbeads, cosmetics, and personal care products.[154] It is estimated that over 80–90% of the MPs found in aquatic environments are derived from land-based sources, including everyday items like plastic bags, bottles, toiletries, clothes, and construction supplies. Additionally, bottom ash produced by plastic incinerators is another terrestrial source of MP pollution. Every element of the ecosystem is impacted by MPs, which are widely distributed and come in various forms, polymers, sizes, and concentrations in freshwater and marine environments, the atmosphere, drinking water, and food.[155] The MP's highly persistent nature, small particle size, and widespread distribution allow them to remain in the ecosystem for long periods of time. Furthermore, they are more likely to act as vectors for hazardous substances like polychlorinated biphenyls and polybrominated diphenyl ethers.[156,157] Their high specific surface area enables them to adsorb various other pollutants including heavy metals, organic compounds, and pesticides, potentially forming new composite pollutants with unidentified adverse effects.[156,157]

It is possible to eliminate the larger MP particles through screening systems (pre-treatment); however, eliminating smaller MP particles is a great challenge and requires multiple treatment procedures. Several conventional, non-conventional, and hybrid techniques for removing MPs are proposed in some research. Three general methods, namely physical, chemical, and biological, can be applied to eliminate MPs from

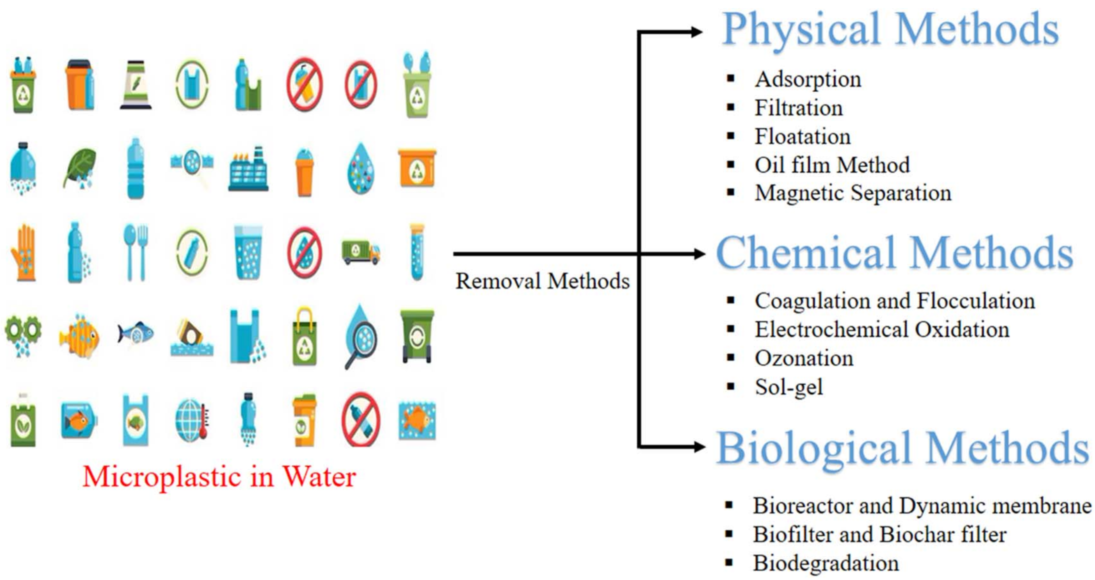


Fig. 8 Overview of the methods used for MP removal from water.

aquatic environments. As depicted in Fig. 8, various techniques including adsorption, filtration, coagulation, magnetic separation, electrochemical degradation, and biodegradation are employed within these categories.[24] However, many of these conventional methods are inefficient due to their various disadvantages. For instance, filtration techniques produce secondary sludge, and the membranes can become fouled over time.[158] In the case of magnetic removal, the process requires the use of magnetic materials, which can cause brittle MPs to break apart.[159] The coagulation process is suitable only for a limited range of MPs and also produces secondary sludge.[160] Electrochemical oxidation, however, requires costly electrodes and results in a decrease in the pH of water during MP removal.[161] Photocatalytic degradation demands high energy inputs, and the photocatalysts are difficult to recover.[162] Biodegradation, although effective, is often a slow process and sometimes leads to secondary pollutants.[163] Many of these approaches work well under controlled laboratory conditions, but their effectiveness decreases significantly when implemented on an industrial scale. This challenge becomes more prominent in complex wastewater systems, where the presence of co-pollutants including, oils, suspended solids, and surfactants can disrupt the treatment mechanism and reduce the oxidation efficiency. Physical and chemical methods also require continuous energy inputs, regular use of chemicals, and regular maintenance, all of which increase operational costs and raise concerns regarding long-term sustainability. Furthermore, these processes generate secondary by-products, which demand further handling and disposal, adding to the ecological and economic burden.[164] Adsorption proves particularly effective in such circumstances as it does not require high pressure, expensive equipment, and additional chemicals. Owing to its passive nature and surface-driven mechanisms, adsorption remains more adaptive to dynamic changes in wastewater compositions. Biochar-based adsorption holds great potential due to its high porosity, presence of diverse surface functionalities, and high affinity for hydrophobic effluents, allowing it to remove MPs more effectively. Furthermore, due to the carbon-rich nature, biochar can be regenerated, reused, or disposed of. Recent experimental studies highlight biochar's potential as a more scalable and feasible solution under harsh conditions.[165] Olubusoye and his coworkers found that column filters filled with the biochar derived from pine wood or sugarcane bagasse can effectively remove 86.6–92.6% of MPs with different forms and morphologies from agricultural runoff.[166] Similarly, Jiang and his colleagues showed that magnetic biochar derived from industrial hemp straw can effectively remove more than 80% of MPs under laboratory conditions, even after five recycling cycles. These findings show that biochar-based adsorption provides substantial cost benefits, is easy to use, and is aligned with sustainability and circular economy principles.[167]

6.2 Adsorptive removal of MP using biochars and their composites

Adsorption technology is one of the most effective approaches for eliminating persistent pollutants, including MPs, from water due to its economic viability, durability, superior efficiency, and simple operational requirements.[168] In the adsorption process, the pollutant (adsorbate) adheres to the surface of the material (adsorbent) until equilibrium is reached. When it comes to using the biochar for MP removal, its large pore volume and abundant functional groups make it an ideal adsorbent. Table 4 presents the MP removal efficiencies, adsorption capacities and recyclability of various adsorbents. Adsorption mechanisms are generally classified into two types: physisorption and chemisorption. Physisorption is governed by electrostatic interactions such as van der Waals forces between the pollutants in the solution and the adsorbent surface,

Table 4 Summary of various adsorbents reported to date for MP removal, highlighting their removal efficiency, adsorption capacities, and recyclability

S. No.	Adsorbents	Removed MPs	Removal efficiency	Adsorption capacity (mg g^{-1})	Recyclability	Ref.
1	Chitin/lignin composite hydrogel	MPs	93.7%	1790.8	3 cycles	170
2	Chitosan–modified alum sludge	Polyethylene (PE)	51.6%	2.67	5 cycles	171
3	EPTAC–modified biochar	MPs	94.7%	463.7	20 cycles	172
4	Chitosan–modified magnetic biochar	MPs	97.2%	15.56	5 cycles	173
5	Polydopamine–modified magnetic algae composite	Polystyrene (PS)	—	223.16	—	174
6	Chitin–cellulose nanofibers	Polystyrene (PS)	93.07%	116.34	4 cycles	175
7	Lily bulb-derived polysaccharide aerogel	Polystyrene (PS)	93.68%	384.615	—	176
8	Iron oxide–biochar composite	Poly (3-hydroxybutyrate-*co*-3-hydroxyvalerate) (PHBV) MPs	98.53%	13.14	4 cycles	177
9	Citric acid functionalized Fe_3O_4 nanocomposites	Polyethylene (PE)	80%	22.886	5 cycles	178
10	Untreated pine pollen grains biosorbent	Polyethylene terephthalate (PET)	95.2%	—	—	179
11	Chitosan–magnetic NPs	Polystyrene (PS)	93%	156.73	5 cycles	180
12	Carboxylated wood-derived cellulose sponges	Polystyrene (PS)	88.8%	586.95	10 cycles	181
13	Loofah plant-derived superhydrophobic sponge	Polystyrene (PS)	99%	381–569	3 cycles	182
14	Polymer-magnetic biochar/zeolite composite	MPs (2 μm)	99%	100	4 cycles	183
15	Coal gasification slag	MPs	99.2%	1400	—	184
16	Dialdehyde-modified aerogel	MPs	97.6%	145.05	8 cycles	185
17	Polyoxometalate nanocluster-infused hydrogels	Polyvinyl chloride (PVC)	95%	—	5 cycles	186
18	CTAB-modified magnetic biochar	Polystyrene (PS)	98%	247	—	187
19	Cow dung biochar	Polystyrene (PS)	92.4%	—	7 cycle	188
20	Modified pine bark biochar	Polyvinyl chloride (PVC)	78%	156.08	—	189
21	Jute stick-activated charcoal	Polyvinyl chloride (PVC)	94.1%	4.4668	—	190

leading to multilayer adsorption. This process is non-specific and reversible, and typically occurs rapidly at lower temperatures and requires minimal activation energy, around 20 to 40 kJ mol^{-1}. The functionality of the physisorption is strongly correlated with the surface area and porosity of the adsorbent. However, chemisorption involves the formation of stronger covalent or electrostatic interactions between the adsorbate and the adsorbent, resulting in a single monolayer at the surface of the adsorbent. This process is highly specific, irreversible, and exothermic, requiring higher activation energy, generally above 80 kJ mol^{-1}.[169]

Various mechanisms contribute to MP's adsorption, such as hydrophobic and chemical interactions, pore filling, electrostatic attractions, and van der Waals forces (Fig. 9). The biochar has a high surface area and a porous structure, which enable it to physically attract and hold MP particles through van der Waals forces. MPs are often hydrophobic, implying that they repel water, and the biochar, particularly when derived from specific feedstocks, can also exhibit hydrophobic surface characteristics. This compatibility makes the biochar highly effective at attracting and adsorbing hydrophobic MP particles.[191] Ahmad and his co-workers identified the primary mechanisms of interaction between jujube-waste-derived biochar and PE, including entrapment in the pores (pore filling), entanglement with flaky structures, and electrostatic interaction. MP particles can enter into the pores located on the surface of porous adsorbents such as biochars and are trapped within the pores. The entrapment mechanism could be predominant in biochar–based adsorbents due to the porous structure.[192] Larger MP particles, which are too big to pass through the pores, are physically captured in the openings and reduce the interference of surface interaction effects, while smaller particles may be adsorbed onto the surface or enter the smaller pores. Wang and his colleagues described the mechanism of action as “stuck”, “trapped”, and “entangled” when simulating the removal of microplastic spheres (10 μm) by corn straw and hardwood biochar filter columns.[193] The spruce bark biochar prepared by Siipola *et al.*[194] using steam activation exhibited larger pores, allowing for 10 μm microplastic particles to be easily retained and settled within the pores. Biochar's surface may possess a negative or positive charge depending on its preparation and the feedstock used. This can lead to electrostatic interactions between biochars and MPs, especially if the MPs have charged functional groups on their surface. The screening effect of

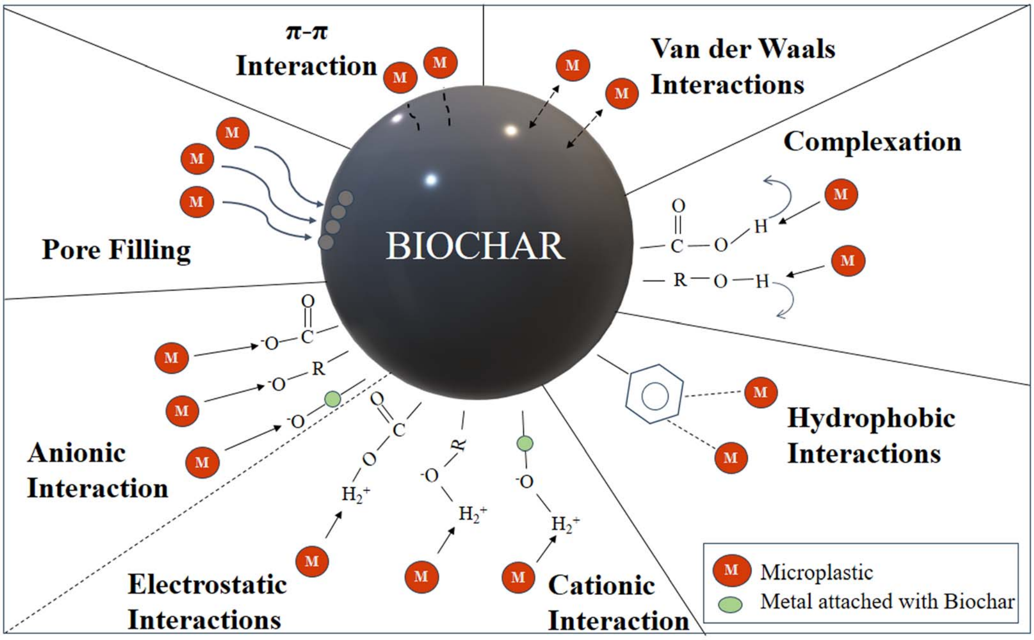


Fig. 9 Adsorption mechanisms underlying the removal of MPs by the biochar.

counterions in high-ionic-strength environments can neutralize the charge on the biochar surface, diminishing the attractive forces between the biochar and the charged pollutants. Studies have shown that MPs exhibit strong hydrophobicity and tend to accumulate at high concentrations.[195] The polarity of biomass weakens during high-temperature pyrolysis, leading to an increase in its hydrophobicity. This is also a significant factor contributing to hydrophobic adsorption.

Physical interception involves filtration and pore filling.[196] MP can be removed by π–π interactions between the functional groups of biochars and MPs. The biochar contains a range of functional groups such as hydroxyl (–OH), carboxyl (–C=O, –COOH), and phenolic groups, which can interact with the surface of MP particles. The π electron cloud of the biochar may be incoherent with the π electron cloud of anions, cations, proton donor functional groups, and aromatic MPs. Valence interactions, π–π bonds, are key to the adsorption of highly aromatic MPs, especially for plastic particles containing benzene rings.[197] Experimental data indicate that different categories of MPs respond more strongly to particular surface chemistries of the biochar. For instance, aromatic MPs like polystyrene (PS) preferentially bind the graphitized biochar

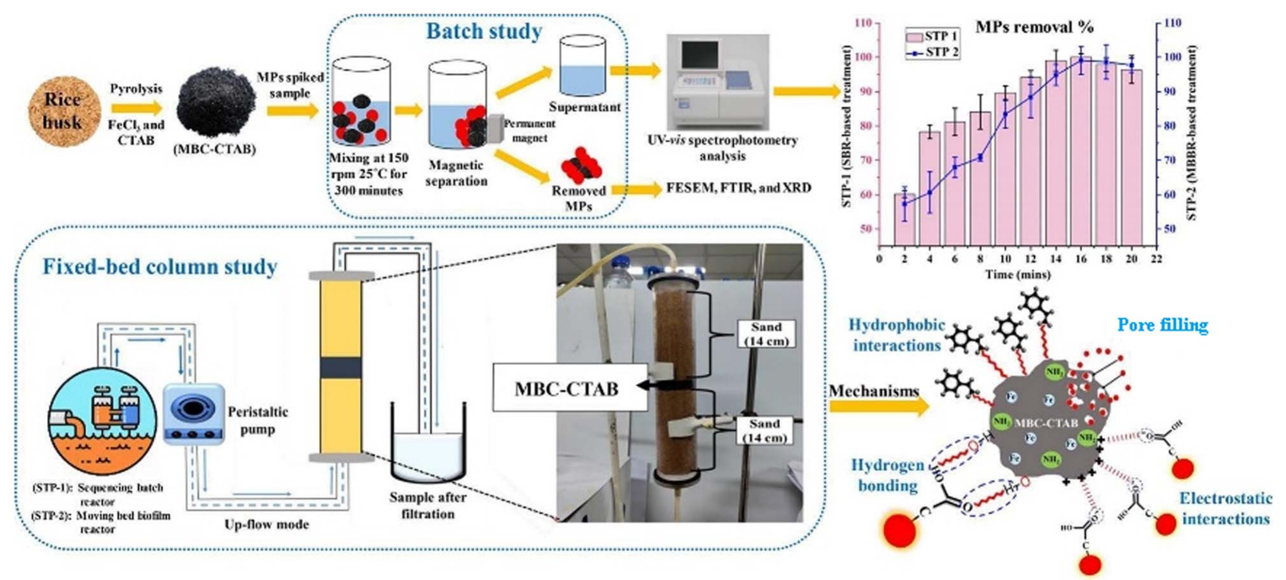


Fig. 10 Synthesis, mechanism and experimental (batch and fixed-bed column) procedures for the CTAB–modified magnetic biochar (MBC–CTAB) derived from rice husk for MP removal. Reproduced with permission from ref. 187, Copyright 2024, Elsevier.

through π–π stacking, while non-polar and highly hydrophobic MPs like polyethylene (PE) and polypropylene (PP) interact more strongly with high-temperature aromatic biochars, where hydrophobic forces and dispersion-type interactions predominate. In contrast, the positively charged or LDH–modified biochar show improved adsorption of negatively charged aged MPs *via* electrostatic attraction, whereas oxidized MPs (*e.g.*, carboxyl-functionalized plastics or PET fragments) exhibit stronger affinity towards the biochar rich in oxygenated functional groups (–OH and –COOH), enabling hydrogen bonding and dipole–dipole interactions.[198,199]

The adsorption process for MP removal can be carried out using either batch or continuous methods. The batch technique is widely favored by many researchers due to its operational simplicity and effectiveness in treating small volumes while maintaining a consistent adsorbent dose.[200] In a continuous

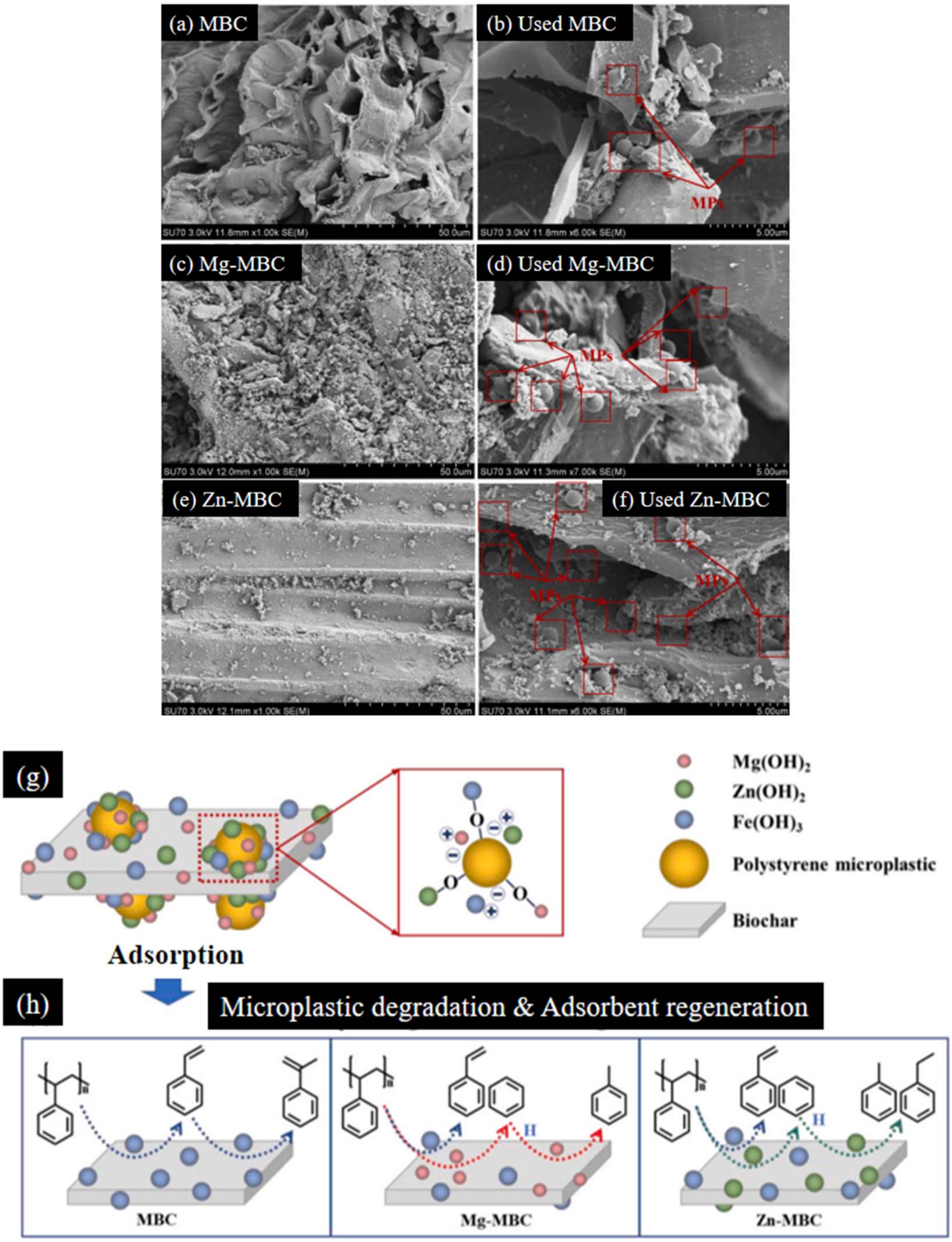


Fig. 11 SEM images of the modified biochar (MBC, Mg–MBC, and Zn–MBC) before and after MP adsorption (a)–(f). (g) Mechanism of MP adsorption over the modified biochar and (h) thermochemical MP degradation and adsorbent regeneration. Reproduced with permission from ref. 201, Copyright 2021, Elsevier.

adsorption system, a fixed-bed column loaded with adsorbent particles is usually employed. In these setups, various factors such as adsorbent's morphology, chemical stability, and durability all have a significant impact on the flow through the column and clogging risk in such a system. The structure and composition of the water matrix, physicochemical features of the adsorbent, and operational conditions like pH, contact time, initial pollutant concentration, adsorbent dose, and temperature collectively affect the overall efficiency of adsorption.[7,168,200] The performance of the adsorption can be quantified using standard expressions for percentage removal and equilibrium uptake.[200]

$$\% \quad \text{Removal} = \frac{(C_o - C_e)}{C_o} \times 100$$

$$\text{Equillibrium} \quad \text{uptake}\ (q_e) = \frac{(C_o - C_e)V}{W}$$

where C_o and C_e indicate the initial and equilibrium concentrations of the MPs expressed in mg L^{-1}, respectively. The term q_e represents the amount of MPs adsorbed at equilibrium (mg g^{-1}), V stands for the volume of the solution (L), and W corresponds to the mass of the adsorbent (g).

Parashar *et al.*[187] synthesized a CTAB–modified magnetic biochar (CTAB–MBC) from rice husk and incorporated it into a sand filter to effectively remove MPs from aqueous media. Batch and fixed column study showed that optimal conditions achieved more than 97% MP removal at pH 4 in 3 min. The adsorption kinetic study followed a pseudo-second-order model, whereas the Langmuir isotherm evaluated the adsorption behaviour with a maximum capacity of 247 mg g^{-1}. Column studies on real secondary sewage effluents showed 98% MP removal using a CTAB–MBC sand filter system at a flow rate of 5 mL min^{-1} and a bed height of 4 cm (Fig. 10).

A research study by Wang and colleagues explored the removal efficiencies of the magnetic biochar (MBC), magnesium–modified magnetic biochar (Mg–MBC), and zinc–modified magnetic biochar (Zn–MBC) for polystyrene MPs in aqueous media, achieving removal rates of 94.81%, 98.75%, and 99.46%, respectively. Additionally, the study suggested that the decreased removal capacity in wastewater was due to the competitive interaction during the adsorption of MPs and anionic dyes. The smaller molecular size of the negatively charged anions from the dyes is thought to block the small micropores of the biochar, competing for the available positively charged adsorption sites (Fig. 11). The competitive adsorption effect significantly influenced the adsorption capacity of Zn–MBC in the presence of $H_2PO_4^-$ and organic materials in real water samples. The study also explored the thermal regeneration process that simultaneously restored the adsorbents and degraded the adsorbed MPs. Even after five cycles, Mg–MBC, Zn–MBC, and MBC retained high removal efficiencies of 94.60%, 95.79%, and 95.02%, respectively, demonstrating the potential of robust, cost-effective, and eco-friendly Mg/Zn–MBCs for MP removal.[201]

7 Challenges and future perspectives

Biochar-based MP removal has garnered considerable attention owing to its sustainability, cost-effectiveness, and versatility; nonetheless, its practical application encounters numerous important hurdles that must be resolved for successful large-scale deployment. The substantial heterogeneity of biochar-based adsorbents derived from various biomass feedstocks is one of the most fundamental challenges. Any variation in the lignocellulosic composition alters the pyrolysis process, which produces biochars with inconsistent porosity, aromaticity, and surface functionalities. Such heterogeneity often leads to irregular adsorption performance, making process standardization a challenge. Although engineered biochars, such as those doped with metallic and magnetic NPs, have shown improved removal efficiency for MPs, they also cause new environmental issues. These modified materials may leach out under low pH or high ionic strength, leading to the risk of secondary contamination. Another persistent obstacle is the biochar's long-term stability and reusable behaviour. In particular, the treatment of real wastewater is challenging because MPs coexist with other co-contaminants, which often occupy adsorption sites, leading to reduced removal efficiencies compared to controlled laboratory studies. Practical and financial constraints also occur on a larger scale, where large-scale biomass sourcing and its transportation, stable pyrolysis conditions, and disposal and reutilization of MP–loaded waste biochars all increase the operational costs and restrict the viability of widespread utilization.

Future research should focus on improving scalable, cheap, and eco-friendly biochar production techniques. This entails selecting biomass that is readily accessible in local areas, optimizing pyrolysis temperature to improve the adsorption performance, and establishing uniform quality control measures to ensure the consistent performance of biochars. Researchers should also evaluate the durability and regeneration capability of biochars over multiple treatment cycles in real wastewater metrics. Developing modified biochars and their composites with high selectivity for emerging pollutants such as pharma compounds and nanoplastics is another promising direction. Comprehensive life cycle studies are required to analyse the overall ecological impact of biochar production and utilization, as well as compare it to conventional materials. Finally, collaboration among scientists, policy makers, and industries will be crucial to scale up the green technology from laboratory scale to commercial level. Supportive regulations and funding agencies can help to introduce biochar into the national wastewater and waste management framework, strengthening its contribution to MP removal and resource recovery.

8 Conclusion

The growing problem of MP pollution in water bodies resulted in an urgent need for effective and sustainable remediation options. This study highlights the advancement of biochars and biochar-based modified adsorbents for the removal of MPs from wastewater. Biochars derived from agricultural leftovers by thermal conversion offer dual advantages – managing solid waste biomass while contributing to water purification in an eco-friendly manner. Biochar's physiochemical features including a wide range of functional moieties, high surface area and large pore volume enable it to interact efficiently with a wide range of pollutants. The utilization of agricultural wastes as a precursor of biochars shows alignment with several United Nations Sustainable Development Goals (SDGs) and circular economy principles. Moreover, the advancement of modified biochars and composites such as nano and polymer-reinforced materials has shown substantial enhancement in adsorption efficiency, selectivity, and overall performance of the material. However, several challenges such as feedstock quality, production costs, and lack of standardization limit the performance of biochar-based adsorbents under real-world conditions. Addressing these challenges is crucial for widespread adoption. Nonetheless, the biochar stands out as a versatile material capable of bridging sustainable waste management to advanced wastewater treatment. Looking forward, strong collaboration among academics, industries, and administrators will be crucial to unlock the full potential of biochars. Future research should also focus on material standardisation, implementation in real-world settings, and development of legal and economic supportive frameworks for widespread adoption. Such integrated measures are required to transform biochars from a lab-scale innovation to a viable green technology that truly turns "trash into tools" for a sustainable and cleaner planet.

Author contributions

Rinki Chaudhary: data curation, writing – original manuscript draft. Gunjan Sangwan: data curation, writing – original manuscript draft. Sanjay Kumar: software, formal analysis. Vivek Sharma: conceptualization, visualization, validation, software, resources, project administration, methodology, investigation, formal analysis, data curation, writing – review, editing.

Conflicts of interest

The authors declare that there are no financial conflicts of interests or personal relationships that could have influenced the findings or interpretation of this work.

Data availability

No new data were created or analyzed in this review. Data sharing is not applicable to this article.

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