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Title page with Author information

Trends in the applications of biochar for the abatement of microplastics in water

Rubaiyana Taskin[1], Remya Neelancherry[1], Brigitte Helmreich[2], Martins O. Omorogie[2,3,4,*]

[1]School of Infrastructure, Indian Institute of Technology Bhubaneswar, Argul, Odisha 752050, India
[2]Chair of Urban Water Systems Engineering, School of Engineering and Design, Technical University of Munich, Am Coulombwall 3, D-85748 Garching, Germany
[3]Department of Chemical Sciences, Faculty of Natural Sciences, Redeemer's University, P.M.B. 230, Ede, 232101, Nigeria
[4]African Centre of Excellence for Water and Environmental Research (ACEWATER), Redeemer's University, P.M.B 230, Ede, 232101, Osun State, Nigeria

**Corresponding Author: mo.omorogie@tum.de, omorogiem@run.edu.ng, dromorogiemoon@gmail.com*
ORCID: https://orcid.org/0000-0001-9697-2960

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Author contributions

Rubaiyana Taskin: Data curation; Investigation; Formal analysis; Methodology; Resources; Software; Validation; Visualization; Writing–original draft. **Prof. Remya Neelancherry:** Project administration; Investigation; Methodology; Supervision; Validation; Writing–review and editing. **Prof. Dr. Brigitte Helmreich:** Funding acquisition; Resources; Supervision; Writing–review and editing. **Martins O. Omorogie:** Conceptualization; Data curation; Funding

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Availability of data and materials

The Authors confirm that all relevant data are included in this paper.

Declarations

Competing interests

The Authors have no relevant financial or non-financial interests to disclose.

Abstract

The extensive use of plastic materials in modern society has led to the pervasive release of microplastics (MPs) and nanoplastics (NPs). These plastic particles have infiltrated diverse environmental matrices and biological systems, posing serious risks to ecosystems and human health, including endocrine disruption, reproductive issues, and cardiovascular diseases. In response, global attention has turned towards effective remediation strategies. Among these, biochar, a carbon-rich material derived from biomass, has emerged as a promising solution due to its high surface area, adaptable surface chemistry, cost-effectiveness, and potential to valorise waste. This review comprehensively summarizes recent advances in the use of pristine and

modified biochar for MP remediation from water. It also explores future pathways, including the application of biochar in synergistic technologies integrating photocatalysis, membrane filtration, advanced oxidation processes, constructed wetlands, microbial horizontal gene transfer, and data-driven approaches using machine learning and artificial intelligence. The review aims to enhance understanding of the underlying adsorption mechanisms involved in MP mitigation by biochar, as well as the governing forces, based on the most recent research literature. It identifies key limitations in biochar application and outlines strategic directions to address these challenges. Additionally, it discusses biochar's pivotal role in advancing circular economy principles and promoting environmental sustainability, emphasizing its multifunctionality as both an adsorbent and a soil enhancement material. This comprehensive review not only underscores the urgency of addressing plastic pollution but also positions biochar as a vital and promising component in the development of next-generation remediation technologies, contributing to climate change mitigation and fostering a sustainable planet.

Highlights

- Critical elucidation of biochar as a benign solution for microplastic mitigation.
- Comprehensive adsorption mechanisms and biochar modification interactions.
- Future perspectives on sustainable technologies for microplastics remediation.
- One-point guide and strategies for a microplastics-free environment.
- Envisions data-driven remediation using machine learning and AI.

Keywords*:* Microplastic remediation; Biochar applications; Adsorption mechanisms; Advanced oxidation processes; Wastewater treatment technologies

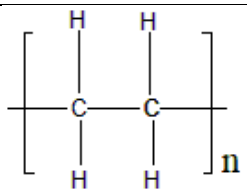
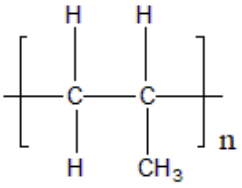
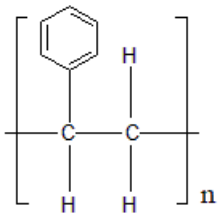
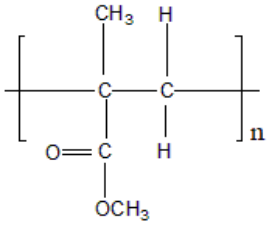
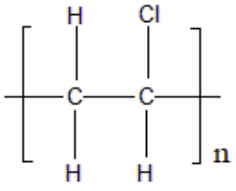
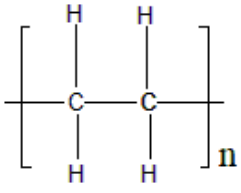
1.0 Introduction

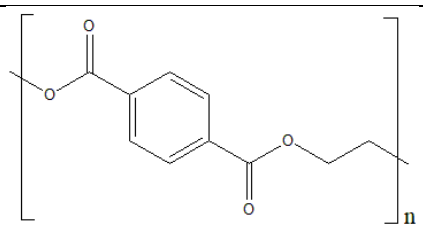
As the world advances rapidly towards unprecedented levels of development and growth, the role of plastics has become integral to modern society. From packaging to infrastructure, plastics are woven into our daily lives, shaping industries and fueling innovation. Plastics are not only ingrained in our daily lives but also serve as pivotal components across numerous industries, driving innovation and shaping our economies. Their multifaceted applications highlight both the opportunities and challenges that lie ahead as we strive for sustainable solutions in an

increasingly plastic-dependent world. In contemporary indoor environment, the prevalence of plastic materials is undeniable. Observations reveal that nearly every room contains at least one item composed of plastic, underscoring the ubiquitous nature of this versatile substance. Since the 1950s, reports from the United Nations (UN) cite that a staggering 9.2 billion tons of plastic have been manufactured. Of this amount, 7 billion tons have entered the waste stream, overwhelmed landfills and contaminated our lakes, rivers, soils, and oceans. The global production and consumption of plastics reaches 430 million tons annually, with approximately two-thirds of this volume ultimately contributing to waste ((UNEP), 2025b). According to UN reports, an alarming 19 to 23 million tons of plastic waste infiltrate aquatic ecosystems annually ((UNEP), 2025c). This significant pollution jeopardizes the health of lakes, rivers, and oceans, posing a serious threat to aquatic biodiversity. Plastic pollution poses significant threats to ecosystems by altering habitats and disrupting natural processes, thereby compromising the capacity of these systems to adapt to climate change. This disruption has far-reaching implications, directly affecting the livelihoods, food security, and overall well-being of millions. Further, the manufacture of plastics ranks among the most energy-demanding industrial processes worldwide. In 2019, plastic production was responsible for emitting 1.8 billion metric tons of greenhouse gases, which represents 3.4% of the global total emissions. Alarmingly, 90% of these emissions stem from the production of plastic and the conversion of fossil fuels ((UNEP), 2025a). While plastic is deeply ingrained in contemporary life, it poses critical challenges related to its environmental impact, its role in climate change, and the sustainability of our future.

Plastics are composed of long-chain organic polymers formed by the process of linking smaller molecules known as monomers. Plastics are utilized significantly in all industries because of their varied qualities, including flexibility, durability, availability in an extensive spectrum of colours, and their resistance to corrosion. Polyethylene (PE) is used for packaging, polypropylene (PP) for food containers, polystyrene (PS) for insulation, polyvinyl chloride (PVC) for pipes, and polyethylene terephthalate (PET) for bottles. Plastics are crucial in various industries. Some of the most widely utilized plastics, along with their respective structures and properties, are comprehensively summarized in Table 1.

Table 1: Chemical structures, formulae, and properties of some common plastics

Plastics	Chemical Formulae	Chemical Structure
Polyethylene (PE)	$(C_2H_4)_n$	
Polypropylene (PP)	$(C_3H_6)_n$	
Polystyrene (PS)	$(C_8H_8)_n$	
Polymethyl methacrylate (PMMA)	$(C_5H_8O_2)_n$	
Polyvinyl chloride (PVC)	$(C_2H_3Cl)_n$	
High Density Polyethylene (HDPE)	$(C_2H_4)_n$	

Polyethylene terephthalate (PET)	$(C_{10}H_8O_4)_n$	

The increasing prevalence of plastic use has resulted in the emergence of microplastics (MPs), which originate from the gradual breakdown of larger plastic items, posing a significant environmental threat. Persistent contamination of the environment by MPs is now considered to be one of the major environmental challenges of the present century. MPs are tiny particles ranging from sizes less than 5 mm in diameter, whereas nanoplastics (NPs) are plastic particles ranging in size from 1 nm to 100 nm. Environmental MPs are diverse particles that differ in size, density, shape, and chemical composition. They are classified as "primary MPs," which are particles less than 5 mm created from sources like industrial pellets, fibers, microbeads, and abrasives used in cosmetics and cleaning products. Once released into the environment, primary MPs may degrade through physical, chemical, or biological processes, including UV exposure and abrasion. This results in "secondary MPs," which are an abundant type of plastic debris found in the environment and have irregular shapes and sizes (Rodríguez-Seijo & Pereira, 2017). MPs are further broken down into NPs in the environment (Zhao et al., 2022b).

As we engage with our surroundings, it becomes imperative to evaluate the role of plastic in our lives and the possible consequences of its pervasive presence. Human exposure to MPs can occur through the ingestion of contaminated food and beverages, inhalation of airborne particles, and direct skin contact. These routes of exposure raise serious concerns regarding the threat of MPs as a cause of inflammation, disruption of endocrine functions, and induction of other negative health outcomes. Emerging research indicates that specific chemicals and additives present in plastics, as well as those employed during their manufacturing, function as endocrine disruptors. These compounds may contribute to hormonal imbalances, reproductive issues, infertility, and elevated risks of renal diseases and various cancers. Furthermore, there is increasing evidence linking exposure to these plastic-derived chemicals with dyslipidemia, insulin resistance, obesity, and diabetes, each of which serves as a significant risk factor for cardiovascular diseases (Rajagopalan & Landrigan, 2021). The World Health Organization (WHO) underscores that the

plastic crisis is fundamentally a public health issue, highlighting that plastic pollution exacerbates the intertwined challenges of climate change, biodiversity loss, and environmental degradation, all of which pose significant risks to human health. Extensive scientific research has revealed numerous health risks and potential adverse effects associated with every phase of the plastic life cycle. These negative impacts are particularly pronounced for the most vulnerable communities, including children and pregnant women ((WHO), November 2024). A recent report published by WHO investigated the presence of MPs in drinking water. In freshwater sources, particle concentrations were found to range from approximately 0 to 10^3 particles per liter. In contrast, drinking water samples—typically analyzed using smaller mesh sizes—showed individual sample concentrations ranging from 0 to 10^4 particles *per* liter, with mean values between 10^{-3} and 10^3 particles *per* liter ((WHO), 2019).This necessitates the urgent need to develop innovative and sustainable approaches for the removal and remediation of MPs. Considering the adverse effects of MPs and their escalating prevalence in the environment, extensive research is being conducted to develop effective remediation strategies. The remediation techniques of environmental MPs can be broadly classified into chemical, biological, physical, integrated and novel approaches as illustrated in Figure 1.

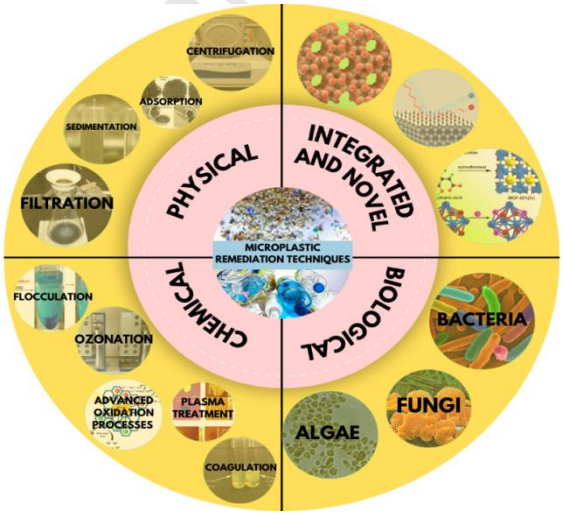


Figure 1: Comprehensive overview of MP remediation methods.

Some of the widely used chemical methods include coagulation-flocculation-sedimentation (CFS) and advanced oxidation processes (AOPs) such as ozonation (John et al., 2023). Bioremediation technology can be categorized into two key types: the biodegradation of MPs by microbial organisms like bacteria, algae, and fungi (Ebrahimbabaie et al., 2022), and the

absorption of MPs by different marine species, including animals, seagrasses, and macrophytes. Physical methods, *e.g*., membrane filtration, sedimentation, centrifugation, and adsorption, are the most commonly used techniques for removing MPs due to their effectiveness, high removal efficiency, and straightforward application (Bamigboye et al., 2024). Integrated innovative methods encompass the combination of multiple remediation techniques to enhance MP removal efficiency. Various research findings highlight the effectiveness of integrated approaches for MP removal in aquatic environments.

While some of the technologies discussed above demonstrate significant effectiveness in the removal of MPs and NPs, several limitations have also been identified. These include sludge generation, equipment maintenance challenges, high energy requirements, suboptimal efficiency, and the probability of secondary pollution (Ji et al., 2024). Ensuring robust structural stability, reusability, and efficient separation of the materials is essential to minimize the risk of secondary pollution (Wei et al., 2025). In comparison to other techniques, adsorption emerges as a particularly efficient method for the removal of MPs and NPs, owing to its high removal efficiency and the notable absence of sludge byproducts, making it a more environmentally conscious alternative (Mota et al., 2025).

Adsorption is recognized as one of the most extensively researched and widely implemented methods for removing MPs (Omorogie & Helmreich, 2024b). Various adsorbents, such as activated carbon, nanoparticles, graphene-based materials, and biomaterials, have been widely explored for the efficient removal of emerging contaminants from wastewater (Pan et al., 2020). Nevertheless, the adsorption materials must be cheap and easily available. The generation of municipal solid waste is projected to increase from 2.1 billion tons in 2023 to 3.8 billion tons by 2050, according to a UNEP report published in 2024 on the “Global Waste Management Outlook 2024.” ((UNEP), 2024). Amid growing concerns regarding plastic pollution, estimates suggest that, without immediate intervention, this figure could triple by 2060 ((UNEP), 2025b), resulting in severe consequences for ecosystems and human health. The systematic development and structural tailoring of functional materials underpin advancements in both emerging energy solutions and pollutant abatement technologies (Zhang et al., 2025b). Biochar presents a compelling solution for both waste management and MP remediation. Its production benefits from easily accessible feedstock, the potential use of waste materials, and its reusability for

multiple cycles. This makes the study of biochar and integrated approaches particularly promising compared to conventional remediation methods. Among the adsorbents, the application of biochar has garnered considerable attention, particularly addressing its adsorption mechanisms for MP remediation.

This review paper aims to provide a comprehensive overview of recent advancements in the use of biochar and its modified analogues or activated forms of biochar for the remediation of MPs in water, highlighting its potential to support circular economy and sustainability goals. The review focuses on four key areas: (i) a summary of various adsorbents used for MP remediation, with emphasis on biochar as a sustainable option derived from waste feedstock; (ii) production and modification techniques that enhance biochar's ability to adsorb various contaminants, especially MPs, while promoting the use of waste resources; (iii) the adsorption mechanisms involved in MP capture by biochar, including the different forces and interactions that govern the process; and (iv) the significant role of biochar in advancing circular economy strategies, not only as a pollutant adsorbent but also as a multifunctional material that enhances soil health, supports resource recovery, and contributes to long-term carbon sequestration and climate mitigation.

2.0 Understanding the adsorption process and uptake of various MPs

2.1 Forces governing adsorption

Adsorption of MPs is a viable and effective remediation method that offers high removal efficiency, the versatility to use various adsorbent materials, and the potential to utilize waste materials as adsorbents, aligning with the principles of a circular economy. Adsorption is generally classified into two primary categories: physical adsorption and chemical adsorption (Zhao et al., 2022a). In MPs removal, physisorption, which relies on weak van der Waals forces and hydrophobic interactions, is primarily seen in passive filtration systems, offering rapid kinetics but limited selectivity (Wang & Guo, 2020). Chemisorption involves stronger interactions, such as covalent and hydrogen bonding, often facilitated by engineered adsorbents like oxidized biochar or amine-functionalized polymers, providing irreversible binding and enhanced specificity for nano- and micro-scale plastics (Wang et al., 2021a). Physical adsorption

occurs at relatively low temperatures, exhibits non-selective adsorption, has high adsorption rates, and involves a low heat of adsorption (Thommes & Cychosz, 2014). Chemical adsorption is characterized by its dependence on elevated temperatures for the reaction to occur. Additionally, it demonstrates a degree of selectivity in its interactions (Lu et al., 2023), which enhances the concept of selectivity for the adsorption of specific MPs.

2.2 Performance parameters

Adsorption efficiency and capacity are critical parameters for assessing the performance of an adsorbent. Adsorption efficiency refers to the percentage of the adsorbate removed from the original solution. It can be calculated using the initial and final concentrations of the adsorbate and is often expressed in percent removal (%). Conversely, adsorption capacity refers to the mass of adsorbate that can be absorbed by a unit mass (or volume) of the adsorbent, commonly expressed in milligrams *per* gram ($mg.g^{-1}$) (Lu et al., 2023).

2.3 Recent advances in adsorbents for MPs

Various adsorbents have been utilised for the remediation of MPs, but it is noteworthy to mention that biochar has been extensively investigated as an effective adsorbent for removing various emerging contaminants, including MPs. Table 2 summarizes a range of adsorbents employed to remove MPs, highlighting their removal efficiencies and applications. Recent research has shown removal efficiencies of up to 100% for PS using biochar derived from spent coffee grounds produced at 500 °C (Torboli et al., 2025). This finding underscores the effective conversion of waste materials into valuable products for the remediation of other contaminants. Another investigation has utilized dewatered sludge (aluminum-rich) and waste-activated sludge to remove Polystyrene Nanoplastics (PS-NPs) and PE, respectively (Sun et al., 2023b; Wang et al., 2022a). An extensive variety of adsorbents have been employed for the removal of specific MPs. Notably, environmentally friendly modified fly ash with iron ions has been utilized for the effective removal of PS-MP (Zhao et al., 2022a). Moreover, magnetic carbon nanotubes exhibit remarkable removal efficiencies of up to 100% for MPs such as PET, PE, and polyamide (PA) (Tang et al., 2021). In addition, chitin sponges have demonstrated efficiencies ranging from 72%

to 92% in removing PS, highlighting the potential of biopolymer-based adsorbents in addressing MP pollution (Sun et al., 2021). Biochar-derived adsorbents have demonstrated remarkable efficacy in the removal of MPs, underscoring the necessity for a recent comprehensive review of biochar in the context of MP remediation within aqueous environments.

Table 2: Overview of various adsorbents used for MP removal: adsorption efficiency, capacity, and experimental conditions

Adsorbent	MP	MP size (μm)	Removal efficiency (%)	Adsorption capacity ($mg.g^{-1}$)	References
Loofah Plant Derived Sponge	PS	5	99	381–569	(Li et al., 2023)
Oat Protein Isolate Derived Sponge	PS	1	81	10.9	(Wang et al., 2021b)
Polyethyleneimine Coated Cellulose Fibers	PMMA, PVC	0.05–0.137	~99	0.8–0.86	(Batool & Valiyaveettil, 2021)
Sponges based on Chitin-loaded with GO or O-C_3N_4	PS, PS-COOH PS-NH_2 ,	0.896–1.14	72–92	3.33–12.9	(Sun et al., 2021)
3-D Reduced Graphene Oxide Aerogel	PS	5	66−89	119–534	(Yuan et al., 2020)
Polydopamine-Enhanced Magnetic Chitosan Aerogels	PS, PE, PET	Not Reported	92 95 97	62–127 47–130 125–132	(Zheng et al., 2022)
Livestock manure	Polyhydroxyalkanoat	0.2, 2	22−31	Not Reported	(Tong et al., 2020)

biochar	e PHA-MPs				
Cellulose Nanofiber Aerogel Modified with Quaternary Ammonium Salt	PS	1	~99	146	(Zhuang et al., 2022)
Activated Carbon Electrode	PS	0.04	Not Reported	322–707	(Xiong et al., 2020)
Phosphoric acid/Amino-zeolite Biochar	PS	6	96–97	4.78–4.85	(Omorogie & Helmreich, 2024a)

Adsorption has emerged as a highly effective and sustainable strategy for the remediation of MPs, governed by physical and chemical interactions that control selectivity and capacity. Recent advancements in the development of engineered adsorbents highlight their potential as innovative materials for applications that have high efficiency and reflect the principles of a circular economy.

3.0 Adsorption of MP onto biochar

3.1 Biochar production

Biochar is a carbon-rich material produced from organic feedstock under thermal combustion at varying temperatures with a limited oxygen supply (Lehmann & Joseph, 2015). Biochar is produced through pyrolysis, a high-temperature process that valorizes solid residues by converting biomass into valuable products, with biochar being one of the key products (Mota et al., 2025). Figure 2 shows the products of pyrolysis that are bio-oil (a mixture of hydrocarbons), synthetic gas (a mixture of hydrocarbon gases), and biochar (a solid fraction) (Tomczyk et al., 2020). Figure 2 also elucidates that an array of waste products is utilized as feedstocks, which include lignocellulosic materials sourced from forests, agriculture, agricultural waste, and the

food industry, such as crop residues, wood, food waste, animal feed, and municipal waste, which enhance the circular economy by converting trash into treasure. Thermal treatment or process of biomass can be divided into gasification, torrefaction, and pyrolysis. Pyrolysis of biomass can also be divided into slow, fast, and medium pyrolysis. Chars are produced through slow pyrolysis, with a residence time ranging from minutes to hours (Siipola et al., 2020). Table 3 provides a detailed overview of the various pyrolysis processes, along with their corresponding products and conditions. Table 3 reveals, intermediate pyrolysis conditions produced a greater biochar yield of 40% compared to slow or fast conditions. Elevated heating rates impact heat and mass transfer, thereby influencing the production ratios of volatiles and intermediates (Kambo et al., 2015).

Table 3: Different products of pyrolysis with slow, fast, and intermediate pyrolysis (Siipola et al., 2020)

	Pyrolysis conditions		
	Slow	Intermediate	Fast
Temperature(^{o}C)	400	400	500
Residence Time (h or s)	1-5 h	10-20 s	< 1s
Char (%)	12	40	12
Liquid(%)	75	40 (2 phases)	75
Gas(%)	13	20	13

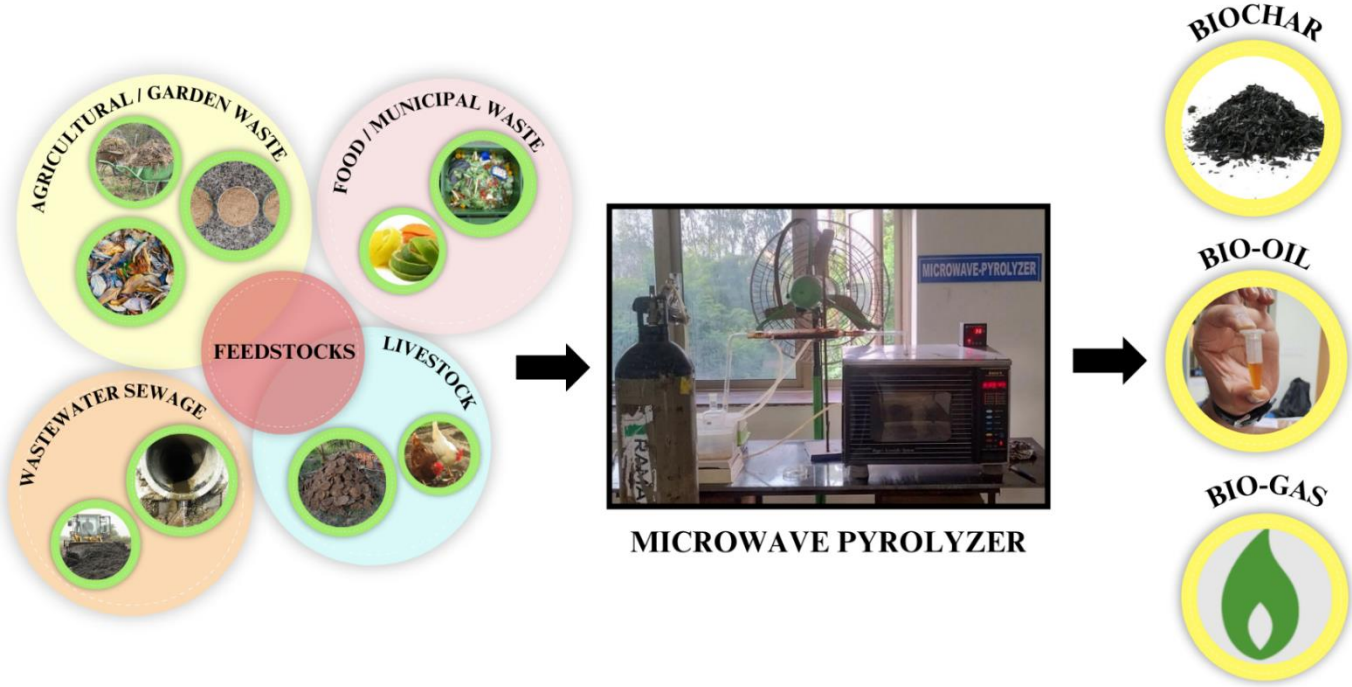


Figure 2: Schematic representation of feedstocks and products in microwave-assisted pyrolysis.

Biochar derived from carbon-rich sources, like agricultural biomass and residues, produced at higher temperatures of 400 °C and 700 °C typically demonstrates increased specific surface area, pore volume, and aromatic structural characteristics (Liu et al., 2021b). To optimize these properties, it is strategically advantageous to select feedstocks that are high in lignin and low in ash content (Li et al., 2023). Biochar's effectiveness in MP remediation can be enhanced through tailored production methods and modifications, as discussed in the next section. For instance, Ganie et al produced biochar from sugarcane bagasse at pyrolysis temperatures of 350 °C, 550 °C, and 750 °C for NP adsorption. The biochar generated at 750 °C demonstrated the highest efficiency, removing over 99% of NP within 5 min and achieving an adsorption capacity of 44.9 $mg.g^{-1}$,owing to its greater surface area (540 $m^2.g^{-1}$) and porous structure (Ganie et al., 2021). Also, Garfansa et al revealed that hardwood biochar achieved exceptional removal efficiencies of 96.82% for PS10-15 (polystyrene, 10–15 μm, irregular, white), 95.52% for PET6-9 (polyethylene terephthalate, 6–9 μm, spherical, red), 95.92% for PA5 (polyamide, < 5 mm, fibrous, blue), and 95.12% for PSnano (polystyrene, 350–860 nm, irregular, white), underscoring Biochar’s significant efficacy in MP filtration applications (Garfansa et al., 2025).

3.2 Biochar´s modified analogues or activated forms of biochar

Biochar modifications offer significant improvements to its structural and physicochemical characteristics. The interactions between biochar and the pollutants influence the overall adsorption capacity. Enhancing the performance of biochar may involve efforts to increase its surface area, develop functional groups that contain oxygen, and improve the degree of aromaticity (Wang & Chen, 2006). The size of the pores and the types of surface functional groups present in biochar are critical characteristics that affect its efficiency as an adsorbent for pollutants. The specific surface functional groups significantly enhance the biochar's ability to adsorb certain pollutants (Díaz et al., 2024). Such improvements or modifications greatly enhance the capacity of biochar to adsorb various contaminants, notably organic pollutants and emerging contaminants such as MPs.

Biochar can be modified or activated through physical, chemical, or biological methods, as comprehensively detailed in Figure 3. While biological methods, including microbial treatment and enzymatic modification, show promise for environmentally friendly biochar modification, physical and chemical activation methods have been more thoroughly researched and implemented due to their efficiency, scalability, and the precise control they offer over biochar properties, such as surface area, porosity, and functional group composition (Matyasik et al., 2025; Tan et al., 2015; Wang & Wang, 2019).

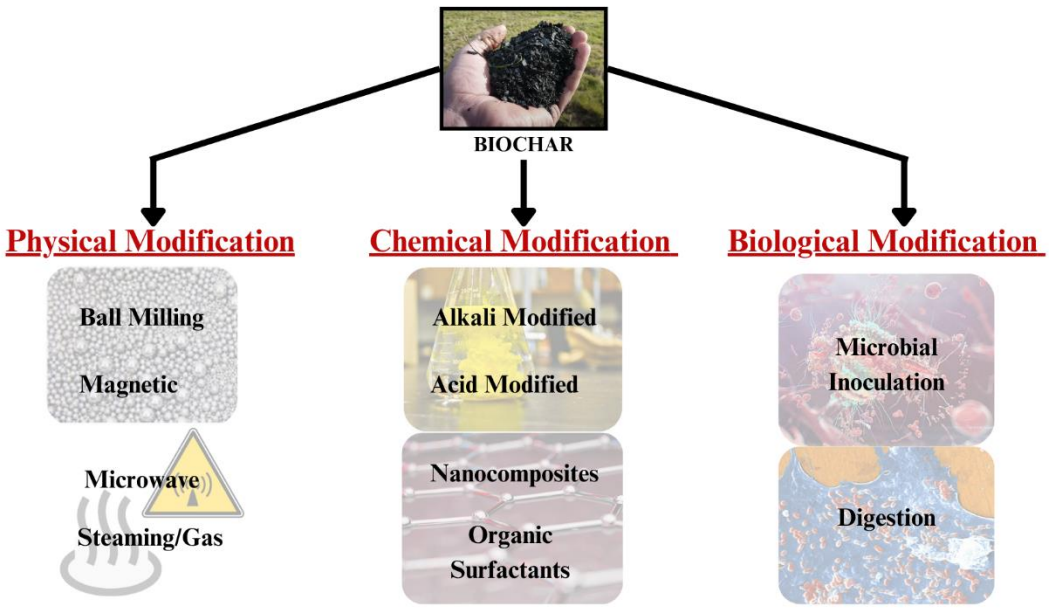


Figure 3: Classification of techniques for biochar modification.

3.2.1 Physical modification

Physical modification of biochar encompasses the alteration of its structural and morphological attributes through non-chemical approaches. The primary aim of these interventions is to enhance physicochemical properties such as surface area, pore volume, and porosity distribution. Such modifications significantly elevate the reactivity and adsorption capacity of biochar, thereby optimizing its interaction with target pollutants, while preserving its inherent chemical composition. The most commonly employed techniques for physical activation include steam activation, gas activation, ball milling, the use of magnetic properties, and microwave-assisted activation (Banerjee et al., 2016). Microwave pyrolysis has emerged as a highly effective technique, using microwave heating to swiftly elevate temperatures while minimizing energy consumption without direct contact with the material. Compared to conventional heating methods, microwave pyrolysis is more environmentally sustainable and has become the predominant technique in conventional pyrolysis applications. The process of modified pyrolysis can greatly improve the porosity and surface area of biochar, enhancing its sorption capacity. The use of K_3PO_4 in combination with clinoptilolite or bentonite as microwave absorbers and catalysts can enhance the microwave absorption efficiency and lead to improved quality of the biochar generated from the pyrolysis of switchgrass (Liu et al., 2022).

Gasification involves partially oxidizing raw materials using agents like air, oxygen, or steam, typically conducted at temperatures exceeding 700 °C and requiring minimal amounts of steam and oxygen (Hansen et al., 2016). Steam-modifying biochar primarily aims to improve its specific surface area, pore volume, and surface characteristics by decreasing its aromatic content and polarity (Liu et al., 2022). Steam pyrolysis and hydrothermal carbonization representfavorable techniques for the sustainable production of biochar, offering a lower environmental impact. These processes facilitate the dissolution of nitrogen oxides and sulfur oxides in water, contributing to decreased air pollution as compared to conventional practices of biochar production. Furthermore, the absence of a pre-drying requirement leads to lower energy consumption and reduced greenhouse gas emissions (Bai et al., 2022). A very recent research demonstrated that coal gasification slag-based adsorbent exhibited remarkable capabilities for the removal of MP, achieving an adsorption capacity of up to 1,400 $mg.g^{-1}$. The study reported an

impressive adsorption-removal efficiency of 99.2% at an MP concentration of 250 $mg.L^{-1}$ with a dosage of 2.5 g of the adsorbent (Lv et al., 2025). These findings open avenues for further research into the potential of biochar-based adsorbents for similar applications.

Using ball-milling to modify biochar can significantly enhance its ability to adsorb contaminants, as this process increases both the surface area and the availability of active sites on the biochar for the adsorption of MPs. As a result, it improves the efficiency of pollutant removal from water. Ball-milled biochar features a higher concentration of aromatic π-π structures, which improve π-π electron-donor-acceptor (EDA) interactions and enhance its hydrophobic interactions with pollutants (Zhang et al., 2019). Because of its simple and efficient operation, ball milling can significantly improve the adsorption capabilities of modified biochar when integrated with other methods. The surface functional groups present on the biochar facilitate the formation of hydrogen bonds and various interactions with MPs (Shrivastava et al., 2024). In a study by Shi *et al*, magnetic biochar was successfully synthesized by mixing pinewood-based biochars with Fe_3O_4 nanoparticles in a 3:1 mass ratio within an agate pot. The milling was conducted at a speed of 400 rpm for 24 h, with the direction of rotation reversed every 6 h (Shi et al., 2023a). In another study conducted with aqueous solution containing PS microspheres (1 µm, 100 $mg.mL^{-1}$), the removal efficiencies recorded for magnetic biochar, magnesium-modified magnetic biochar,and zinc-modified magnetic biochar were as significant as 95%, 99%, and 99%, respectively (Wang et al., 2021a). Studies demonstrate that magnetic biochar produced from organic waste exhibits significant efficacy in the removal of MPs like PS, PVC, PA, *etc*, utilizing both batch and fixed-bed adsorption techniques. The removal efficiencies achieved for PS removal using magnetic rice husks in batch experiments were determined to be as high as 99.96%, as demonstrated by another study(Wu et al., 2023). Similarly, Li et al developed magnetic biochar from algal biomass for effective removal of granular MPs. The uniform adsorption sites allowed for efficient sorption of PS-MPs on a homogeneous monolayer. Notably, this magnetic biochar can be reused up to five times (Li et al., 2024).Thus, modifying biochar for MP removal can greatly enhance removal efficiency and facilitate the post-treatment separation of spent biochar as well, especially with magnetic modifications.

Although physical modification techniques enhance the structural characteristics of biochar, chemical modification methods, particularly acid-base impregnation, offer more precise control over the surface functionality and composition.

3.2.2 Chemical modification

The predominant method for chemically modifying biochar involves using acid or alkaline treatments. Acid-base impregnation, a process involving sequential or individual treatment with acidic and alkaline solutions, alters the surface characteristics and functional groups (such as carboxyl and hydroxyl groups) of biochar while aiding in eliminating impurities, including ash and metal residues, from the original biochar. (Li et al., 2016). Common chemical activators used in conjunction with heat include NaOH, HNO_3, H_2SO_4, KOH, HCl, K_2SO_4 and $ZnCl_2$ (Liang et al., 2019).

The first step in the acid-chemical activation process is dehydration, in which acidic agents (H_2SO_4, HCl, $ZnCl_2$) eliminate structural water and hydroxyl groups, causing the carbon skeleton to undergo restructuring and form micropores. In addition to removing volatiles and amorphous carbon, concurrent oxidation by HNO_3 or K_2SO_4 increases surface reactivity and prevents tar formation by introducing oxygenated functionalities. Chemical activation techniques present several benefits over physical methods, including the need for lower pyrolysis temperatures, higher biochar yields, increased specific surface area, enhanced micropore development, improved porosity, and greater removal efficiency. Biochar pretreated with H_3PO_4, which demonstrates a notable increase in adsorption capacity, attributed to enhancements in micropore size and specific surface area (Chu et al., 2018). Furthermore, biochar samples that were modified post-pyrolysis with immersion in a 5% diluted HNO_3-H_2SO_4 mixture (1:3, v/v) and heated in suspension at 80 °C for 6 h, not only exhibited a significant increase in specific surface area but also gained oxygen functional groups. This treatment significantly improved the adsorption capacity for PS-based nanoparticles, raising it from 15.5 $mg.g^{-1}$ in the untreated biochar to 18.2 $mg.g^{-1}$ in the modified version (Magid et al., 2021).

Another research demonstrated that the activation of biochar, derived from sycamore bark pyrolyzed at 650 °C using HCl, markedly enhanced its efficacy in adsorbing PS-MPs. While the

unactivated or unmodified biochar (650-BC) exhibited an adsorption capacity of 42.58 $mg.g^{-1}$, the HCl-activated biochar (HCl-BC) achieved a significantly improved capacity of 73.10 $mg.g^{-1}$ (Zhang et al., 2025b). Figure 4a provides a detailed view of the sycamore bark biochar's structure at a magnification of 10 µm, showcasing a relatively smooth surface with minimal porosity. Conversely, Figure 4b illustrates the HCl-modified biochar, which exhibits a markedly more porous and rougher texture. This enhanced surface morphology may facilitate an increased number of active sites for the adsorption of MPs. Following the adsorption of PS-MPs, Figure 4c reveals the concentration of PS-MPs on the pristine sycamore bark biochar surface, whereas Figure 4d highlights a significantly greater accumulation of PS-MPs on the surface of the HCl-BC. The Energy-dispersive X-ray spectra (EDS) illustrated in Figure 4e demonstrate a notable reduction in calcium levels alongside an increase in oxygen content following HCl activation, indicative of the dissolution process of calcium carbonate ($CaCO_3$) (Wang et al., 2024). Concurrently, the X-ray diffraction (XRD) patterns depicted in Figure 4f affirm the initial presence of $CaCO_3$ in the 650-BC sample, with its subsequent loss post-activation attributed to acid-induced decalcification. The enhancement in oxygen levels suggests effective impurity removal, the unmasking of active sites, and surface oxidation resulting from HCl treatment (Liu et al., 2021a).

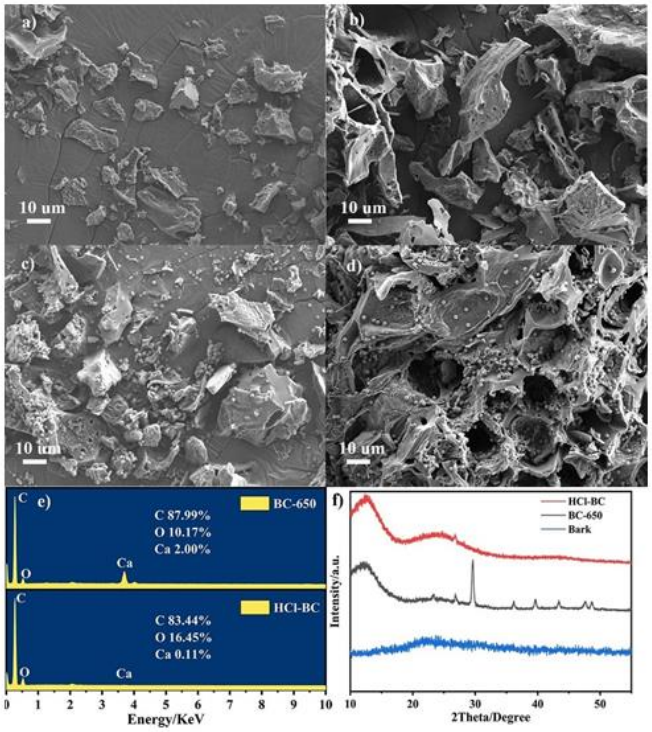


Figure 4: The SEM images of Unmodified sycamore bark Biochar (a,c); HCl Modified sycamore bark Biochar (b,d) before and after adsorption of PS-MPs; EDS spectra of 650-BC and HCl-BC (e); XRD patterns of raw bark, 650-BC, and HCl-BC (f)

(Zhang et al., 2025b).

The adsorption isotherms of PS-MPs on 650-BC and HCl-BC were analyzed using Langmuir, Freundlich, and Sips models as shown in Figures 5a and 5b. The Sips model best fitted the experimental data, exhibiting the highest correlation coefficients. The calculated q_{max} values were 42.58 $mg.g^{-1}$ for 650-BC and 73.10 $mg.g^{-1}$ for HCl-BC, indicating the superior adsorption capacity of HCl-BC. This improvement is attributed to its enhanced surface area and the presence of more oxygen-containing functional groups. The Sips model parameters also reveal a heterogeneous adsorption process with limited active sites at higher concentrations, reflecting the complex nature of PS–biochar interactions (Zhang et al., 2025b). The adsorption of PS-MPs onto biochar is primarily governed by surface complexation, while hydrophobic and electrostatic interactions play secondary roles. Contact angle measurements indicate that HCl-BC is more hydrophilic than 650-BC, and zeta potential analysis reveals a substantially more negative

surface charge, implying electrostatic repulsion with PS. High-resolution X-ray photoelectron spectroscopy (XPS) analysis of C1s spectra shows peaks at approximately 284.8 eV for C–C/C=C, around 286.4 eV for C–O, and 288.7 eV for C=O, with HCl-BC displaying an increased C=O content as depicted in Figure 5c and 5d. O1s spectra at 532.2 eV (C=O) and 533.5 eV (C–O) further confirm the enrichment of oxygenated functional groups, as shown in Figure 5e and5f. These changes result from carbonate removal and the exposure of reactive sites that lead to new oxygen functionalities. Combined with Fourier-transform infrared spectroscopy (FTIR) results, these findings highlight that surface complexation is the primary adsorption mechanism, with HCl activation significantly enhancing biochar's reactivity and PS-MPs adsorption efficiency (Zhang et al., 2025b).

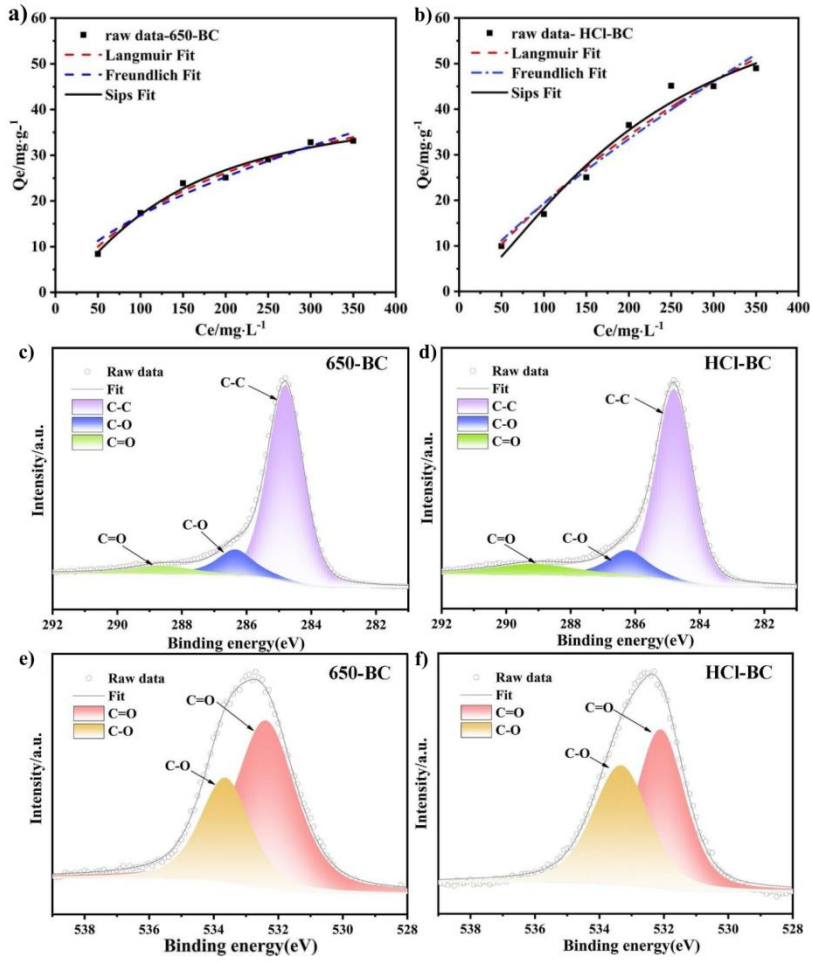


Figure 5: Adsorption isotherms of PS-MPs on 650-BC and HCl-BC (a,b); High-resolution XPS spectra of C 1s (c, d) and O 1s (e, f) regions for 650-BC and HCl-BC (Zhang et al., 2025b).

Modification of biochar by alkaline chemicals such as KOH, Na_2CO_3, NaOH,and K_2CO_3also significantly increases the surface area and porosity of the biochar. This enhancement in porosity is likely to improve the adsorption capacity through pore-filling mechanisms. Furthermore, alkaline modification elevates the abundance of functional groups on the surface of biochar, including —COOH and —OH (Hu et al., 2018). These functional groupsfacilitate surface complexation and reinforce π-π interactions between biochar and MPs/NPs (Sun et al., 2023a). The process of modified pyrolysis can greatly improve the porosity and surface area of biochar, enhancing its sorption capacity. Thus, chemical modification of biochar effectively optimizes its adsorption performance for contaminant remediation.Another imperative study on sulfidized nano-zero-valent iron biochar showed impressive removal efficiencies for dyes and MPs (>90%). It effectively eliminated NPs in under 10 min, achieving a maximum sorption capacity of 128.36 $mg.g^{-1}$ and demonstrating reusability for up to six cycles, indicating its effectiveness for treating industrial wastewater (Ganie et al., 2025).

While chemical modification of biochar precisely engineers its surface chemistry, biological modification utilizes microbial or enzymatic processes to selectively enhance its functionality in ambient conditions. It is considered a much more environmentally friendly method for modifying biochar.

3.2.3 Biological modification

A novel technique for producing cost-effective and efficient biochar-based sorbents involves the biological modification of biochar. The application of microorganisms for the adsorption of contaminants from aqueous solutions has exhibited considerable potential as an economical, straightforward, and effective approach, especially for treating wastewater that contains low levels of pollutants such as heavy metals (Liu et al., 2022).The surfaces of microorganisms contain extensive amounts of functional groups, such as carbonyl, hydroxyl, and amino groups.Biochar surfaces that are abundant in these functional groups, especially oxygenated ones, can significantly encourage interactions like hydrogen bonds with more hydrophilic MPs (Ji et al., 2024). Investigations have highlighted the potential of algal biochar as an effective adsorbent for the removal of diverse organic and inorganic pollutants, including MPs from wastewater (Khan et al., 2022a; Law et al., 2022). In several studies, bacterial conversion or

aerobic/anaerobic digestion was used to biologically pretreat biomass feedstocks for biochar production (Monlau et al., 2015). A study by Li et al revealed that filamentous algae are capable of effectively capturing MPs through processes including entanglement, adhesion, and encapsulation. Furthermore, the research demonstrated that combining Fe_3O_4 nanoparticles with filamentous algal biochar significantly enhances the removal efficiency of MPs. Importantly, it has shown the potential for reusability across five cycles (Li et al., 2024). However, certain studies have demonstrated that algae can rapidly interact with MPs/NPs in aquatic environments, leading to the formation of heterogeneous aggregates. Researchers suggest that by increasing the scale of experiments to encompass larger ecosystems, such as ponds and wetlands, it is possible to effectively simulate and potentially enhance the efficacy of algae in MP removal (Liu et al., 2023). Nanosized biochar has been investigated for its efficacy in removing PS-MPs. These biochars demonstrate significant effectiveness in the adsorption of PS-MPs, achieving optimal removal efficiency at a pH level of 2.0 (Mahmoud et al., 2024). However, more research is needed, particularly on experiments involving biological modification of biochar for MP remediation, as this area has been relatively less explored in the past.Biochar's functionality is sustainably tailored by biological modification. Because biological systems are sensitive to external factors, it is still challenging to obtain consistent results, necessitating exact control over microbial activity and growth parameters.

Although various current biochar modification techniquesdemonstrate potential for MP adsorption, several critical challenges remain to be addressed. These include: (1) unresolved long-term stability of biochar-MP complexes; (2) competitive interference from organic co-pollutants in natural waters; and (3) poor selectivity for sub-micron plastics (<1 μm) due to size-exclusion limitations (Sridhar et al., 2022).

New approaches could involve the use of enzyme-functionalized biochar that targets polymer or MP-specific breakdown, plasmonic biochar hybrids (such as Ag-TiO_2 coatings for photocatalytic degradation) (Sun et al., 2024), and tailored biochar aerogels formarine applications (Cao et al., 2023). Emerging chemical agents that can improve MP adsorption and degradation while addressing sustainability gaps in traditional modification techniques include deep eutectic solvents (Zhang et al., 2024), peroxymonosulfate activators (Qin et al., 2024), and MXene-biochar hybrids (Kumar et al., 2025). To validate scalability, idealised lab settings must be

replaced with standardized field testing procedures utilising environmental samples such as sludge or estuary water.

3.3 Adsorption of MP removal by biochar and its analogues

The removal efficiencies of MPs achieved by various biochar and modified biochar materials, along with key parameters such as feedstock type, pyrolysis temperature, and experimental setup and conditions,are systematically reviewed and summarized in Table 4.

Table 4: Overview of the performance of biochar and modified biochar in MPs removal

Biochar Type	Pyrolysis Temperature (° C)	Pyrolysis Time (h)	Modification (if any)	MP Removed	MP Size (μm)	Removal Efficiency (% or mg·g-1)	Type of Setup of Experiment	Reference
Wood Chips	700	Not Reported	None	PS	1	100 %	Fixed-Bed Column	(Hsieh et al., 2022)
Pinewood Sawdust	700	3	Ball milled at 400 rpm for 24 h	PS-NPs	0.1	80.3 $mg \cdot g^{-1}$	Batch Experiment	(Shi et al., 2023a)
Corncob	500	Not Reported	Modified with Fe-metal using Co-precipitation method	Aged PA	27–307	97 %	Batch Experiment	(Li et al., 2023)
Dewatered Sludge (Aluminium Rich)	480	2	Al, Mg metal modified using Co-precipitation method	PS-NPs	0.08	360 $mg \cdot g^{-1}$	Continuous - Flow Fluidized bed Adsorption System	(Sun et al., 2023b)

Rice Straw	700	1.5	Fe metal modified with Impregnation method	PS-NPs	0.3	90 %	Batch Experiment	(Wu et al., 2023)
Waste Activated Sludge	800	1.5	None	PE	0.05-0.5	Not Reported	Anaerobic Granular Sludge	(Wang et al., 2022a)
Jujube Waste	700	3	None	PE	0–10	99 %	Fixed-bed column	(Ahmad et al., 2023)
Filamentous Algae	600	1	Impregnation with $Fe(NO_3)_3 \cdot 9H_2O$ for 12 h	PS	1	216 $mg \cdot g^{-1}$	Batch Experiment	(Li et al., 2024)
Rape straw	800	2	Ball Milling-Magnetic biochar modified with cetyltrimethylammonium bromide	PS	0.6 – 1	95 %	Batch Experiment	(Shi et al., 2023b)
Lignin	850	2	Fe-modified-*via* Pyrolysis	PS	0.1	68.6 $mg \cdot g^{-1}$	Batch Experiment	(Jiao et al., 2025)
Spent coffee grounds	500	1	None	PS	2–5	100 %	Filtration Column Tests	(Torboli et al., 2025)
Sycamore Biochar	650	Not Reported	None	PS	1	1435 $mg \cdot g^{-1}$	Batch Experiment	(Zhang et al., 2025a)
Sycamore Biochar	650	Not Reported	None	PE	1	706 $mg \cdot g^{-1}$	Batch Experiment	(Zhang et al., 2025a)
Sycamore	650	Not	None	PMMA	1	246 $mg \cdot g^{-1}$	Batch	(Zhang et

Biochar		Reported					Experiment	al., 2025a)
Peanut shell biochar	500	2	None	PS	1	59.1 %	Column Experiment	(Wang et al., 2022b)
Peanut shell biochar	500	2	MgO-Modified using $MgCl_2.H_2O$	PS	1	76 %	Column Experiment	(Wang et al., 2022b)

Table 4 (Continued): Overview of the performance of biochar and modified biochar in MPs removal

Biochar Type	Pyrolysis Temperature (° C)	Pyrolysis Time (h)	Modification (if any)	MP Removed	MP Size (μm)	Removal Efficiency (% or $mg \cdot g^{-1}$)	Type of Setup of Experiment	Reference
Cellulose based Biochar	400	6	None	PS	2	90 %	Column Experiment	(Tong et al., 2020)
Naturally shed sycamore bark	650	2	HCl Modified at 90 °C for 2 h	PS	1	73.1 $mg \cdot g^{-1}$	Batch Experiment	(Zhang et al., 2025b)
Rice Husk	300, 600, 900	Not Reported	Cetyl trimethyl ammonium bromide modified magnetic Biochar	PS	1	97%	Fixed Bed Column Experiment	(Parashar & Hait, 2024a)
Polygonum amphibium	550	Not Reporte	None	Not Reported	0.05	80.3 $mg \cdot g^{-1}$	Batch Experimen	(Cao et al., 2024)

L. (PAL)		d					t	
Saw Dust	550	2	Magnetic Biochar by impregnation with $Fe(NO_3)_3 \cdot 9H_2O$	PS	1	95 %	Batch Experiment	(Wang et al., 2021a)
Saw Dust	550	2	Mg modified magnetic biochar by impregnation with $Mg(NO_3)_2 \cdot 6H_2O$	PS	1	99 %	Batch Experiment	(Wang et al., 2021a)
Saw Dust	550	2	Zn modified magnetic biochar by impregnation with $Zn(NO_3)_2 \cdot 6H_2O$	PS	1	99 %	Batch Experiment	(Wang et al., 2021a)
Activated Hardwood Biochar	700	0.5	KOH Activated for several days at 60 °C	PS	10–15	97 %	Column-Based Sand Experiment	(Garfansa et al., 2025)
Activated Hardwood Biochar	700	0.5	KOH Activated for several days at 60 °C	PET	6–9	96 %	Column-Based Sand Experiment	(Garfansa et al., 2025)
Activated Hardwood Biochar	700	0.5	KOH Activated for several days at 60 °C	PA	< 5000	96 %	Column-Based Sand Experimen	(Garfansa et al., 2025)

							t	
Activated Rice Husk Biochar	400	4	KOH/NaOH Sonicated	PS	10–15	96 %	Column-Based Sand Experiment	(Garfansa et al., 2025)
Activated Hardwood Biochar	700	0.5	KOH Activated for several days at 60 °C	PS	0.35 – 0.86	95%	Column-Based Sand Experiment	(Garfansa et al., 2025)

3.4 Understanding the Adsorption Mechanism of MP on Biochar

The adsorption of MPs onto biochar occurs through a combination of physical and chemical mechanisms. Physical adsorption is primarily governed by electrostatic interactions, while chemical adsorption involves processes such as π-π interactions, hydrogen bonding, and various covalent bonds. The overall adsorption process is influenced by both types of mechanisms, with their relative importance dependent on the specific type of MP and the environmental conditions present. Multiple interaction mechanisms are hypothesized to contribute to the effectiveness of biochar inMPremediation, including π-π interactions, electrostatic attractions, hydrogen bonding, pore-filling processes, hydrophobic interactions, and catalytic roles in pollutant degradation, such as accelerating nitrobenzene reduction, as illustrated in Figure 6.

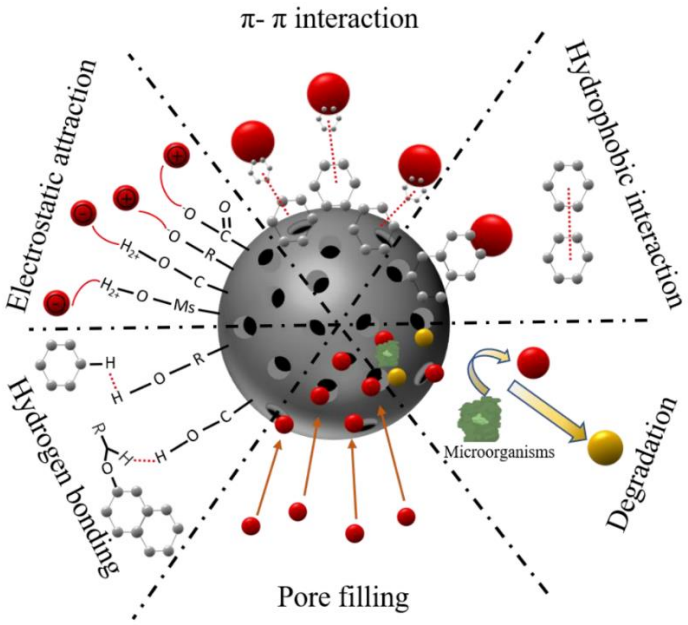


Figure 6: Interactions in the adsorption mechanism of MP removal by biochar (Dong et al., 2023).

Some studies have established that electrostatic interactions play a critical role in the adsorption processes of micropollutants, such as MPs, onto biochar materials. The fundamental and integral principle underlying ionic bond formation is electrostatic interaction, including attractive and repulsive forces. Ionic bonds arise from the electrostatic attraction between anions and cations, which occurs due to the transfer of electrons among atoms (Cheng et al., 2021). Zeta potential measurements reveal that both MPs and biochar exhibit a negative charge (Zhang et al., 2025a). A recent study indicates that, as depicted in the accompanying Figure 7, all three materials-biochar produced by pyrolysis at 650 °C (650-BC), hydrochloric acid-activated biochar (HCl-BC), and PS particles show negative zeta potentials, indicating a predominance of surface acidic groups and negative charge.Notably, HCl activation makes biochar's zeta potential much more negative, attributable to the removal of calcium carbonate and the introduction of additional oxygen-containing functional groups through oxidation (Zhang et al., 2025b). This results in enhanced electrostatic repulsion between HCl-BC and PS particles and suggests that electrostatic attraction is not the predominant mechanism for PS-MP adsorption on HCl-activated biochar surfaces.

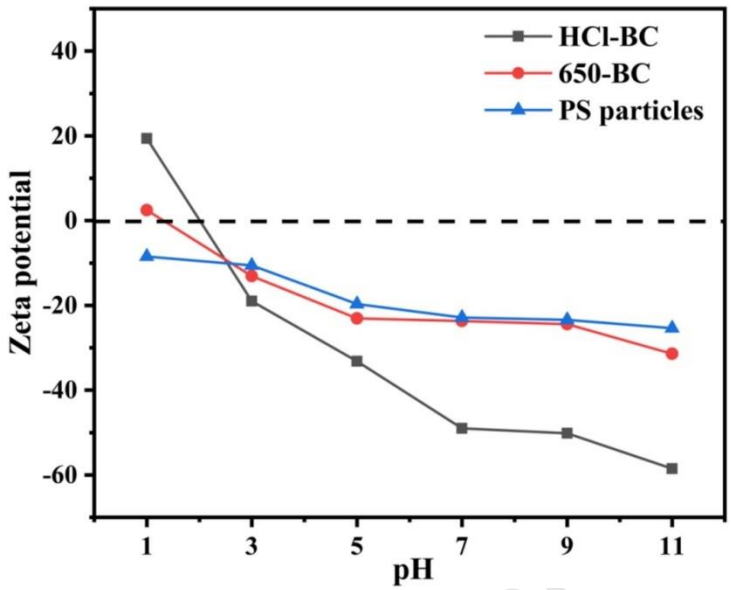


Figure 7: Zeta potential profiles of HCl-BC, 650-BC, and PS-MPs particles measured across a pH range from 1.0 to 11.0 (Zhang et al., 2025b).

Adsorption effectiveness can also be influenced by solution chemistry, as variations in ionic strength and competing salts may alter the electrostatic and hydrophobic interactions between MPs and biochar (Wang et al., 2020). Other recent studies reveal that PMMA has the strongest electrostatic charge, leading to significant repulsion from biochar, which hampers its adsorption capacity. Conversely, PS shows the weakest repulsion, facilitating greater adsorption (Li et al., 2023). This highlights the critical role that electrostatic forces play in the adsorption capacity of biochar.

In another study, Wang *et al* introduced a novel adsorbent composed of Mg/Zn-modified magnetic biochar designed for the removal of PS-MPs. The results indicated that, under neutral pH conditions, both the PS-MPs and the biochar adsorbents exhibited a negative surface charge, aligning with previous studies (Maliwan et al., 2021; Zhao et al., 2021). Therefore, the adsorption of PS-MPs onto the Mg/Zn-modified magnetic biochar was credited to the presence of metal oxides and metal hydroxides on the biochar's surface. These metal constituents developed a positive charge in aqueous environments, thereby enhancing the adsorption of MPs through electrostatic interactions (Wang et al., 2021a).

FTIR analysis provides critical insights into the chemical interactions involved in the adsorption process. Research indicates that MPs can adhere to biochar surfaces *via* hydrogen bonding mechanisms. The blue shift detected in the carbonyl group of biochar, along with the findings from XPS analysis, supports the notion that oxygen plays an active role during the adsorption of MPs on biochar (Parashar & Hait, 2024b). The variations observed in the C-O and C=O peaks across the various MPs indicate that these oxygen-containing functional groups play a crucial role in the adsorption process. Hydrogen bonding occurs between the hydroxyl (-OH) and carbonyl (C=O) groups on the biochar and the corresponding functional groups present on the surfaces of the MPs.Studies indicate that although carbonyl groups can participate in hydrogen bonding due to their oxygen atoms, the rising negative charge on MP surfaces may hinder the capacity of carbonyl (C=O) groups to effectively form these bonds. Conversely, hydroxyl (-OH) groups appear to have a more substantial influence on this hydrogen bonding process (Zhang et al., 2025a). Notably, a hydroxyl functional group identified on modified corncob (HNO_3/H_2SO_4) played a crucial role in the adsorption of PS-MPs onto biochar. This phenomenon is linked to the formation of hydrogen bonds, which helps explain why PS-MPs are adsorbed more effectively onto modified biochar than onto unaltered biochar (Magid et al., 2021). Additionally, the interaction of fluorescent orange amine-modified PS beads (fluo-NP, 100 nm) with coffee grounds was primarily driven by hydrogen bonding between the amine groups on fluo-NP and the hydroxyl and carboxyl groups on the coffee grounds. These interactions were found to be stable across a broad pH range (Yen et al., 2022). Another study revealed that hydrogen bonding also occurs between PS-MPs and goethite, leading to higher levels of PS-MPs adsorption on goethite compared to magnetite (Zhang et al., 2020). Understanding the role of hydrogen bonding and functional groups in MP adsorption on biochar is vital for developing effective strategies to address MP pollution in aquatic ecosystems. XPS further elucidates the electronic states and bonding interactions between biochar and MPs. The C 1s spectra of amino-functionalized zeolite/H_3PO_4-biochar (AFZ) exhibited characteristic peaks corresponding to C–H, C–O, C–C, C–O–C, and O–C–O bonds within the 284.5–289.5 eV range after PS-MPs adsorption, with minor shifts after desorption. These variations confirm the involvement of π–π interactions, hydrogen bonding, and van der Waals forces during adsorption. The O 1s spectra (533–535.5 eV) and survey scan revealed N–H, Si–O, and Al–O bonds, indicating their

participation in the adsorption–desorption process as detailed in Figure 8 (Omorogie & Helmreich, 2024a).

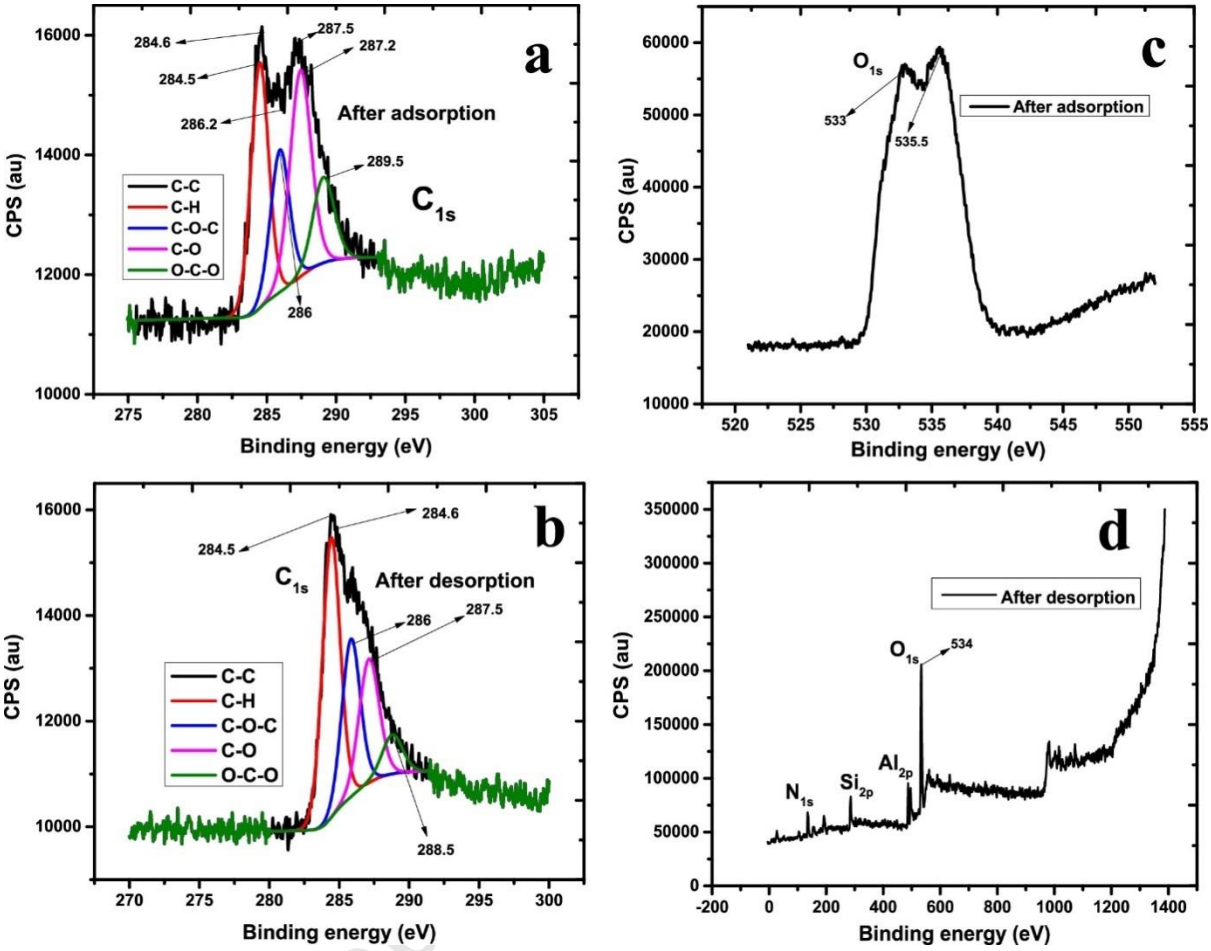


Figure 8: XPS spectra of amino-functionalized zeolite/H_3PO_4-biochar (AFZ): (a) C 1s after adsorption of PS-MPs, (b) C 1s after desorption of PS-MPs, (c) O 1s after adsorption of PS-MPs, and (d) O 1s after desorption of PS-MPs (Omorogie & Helmreich, 2024a).

Density Functional Theory (DFT) analysis provides molecular-level insight into the adsorption process. A recent study by Duan et al showed that while occasional physical immobilization of PS-MPsoccurs, adsorption dominates the overall removal by Fe-doped biochar. π–π interactions and hydrophobic forces contribute substantially due to the aromatic and hydrophobic nature of PS, respectively. Surface functional groups on PS, such as amine and carboxyl groups, enhance adsorption through electrostatic attraction, hydrogen bonding, and complexation, although they partially reduce hydrophobic interactions due to increased hydrophilicity (Duan et al., 2025).

DFT analysis from a complementary study further validates these findings, demonstrating consistency with XPS and FTIR results (Jiang & Hu, 2024). Further experimental validation examining PS-MPs interactions, XPS analysis of biochar reveals a π-π satellite peak at 293.65 eV prior to the adsorption process, indicating the presence of aromatic structures. Following the adsorption of PS, a new peak is observed at 291.65 eV, which can be attributed to π-π interactions between the aromatic rings of PS and the biochar surface (Zhang et al., 2025a). This observed peak shift demonstrates that PS adsorption significantly enhances the interactions between the π-electron clouds of PS and biochar (Shi et al., 2023a). In another study, researchers investigated the effectiveness of a three-dimensional reduced graphene oxide (3D RGO) structure in removing PS-MPs from water. The findings revealed that the 3D RGO displayed a smooth and substantial graphite layer, which promoted π–π interactions that attracted the macromolecular PS-MPs characterized by π electrons. Consequently, the adsorption of PS-MPs onto the surface of 3D RGO was primarily driven by the robust π–π interactions between the carbon rings in the 3D RGO and the benzene rings in the PS-MPs (Yuan et al., 2020).

The characteristics of biochar, such as its specific surface area and the density of its functional groups, are significantly influenced by the pyrolysis temperature. Ganie et al utilized biochar produced from sugarcane bagasse at temperatures of 350 °C, 550 °C and 750 °C, finding that elevated temperatures corresponded with increased specific surface areas and reduced charged functional groups that are negatively charged. Biochar that was produced at 750 °C demonstrated the highest efficiency of adsorption towards negatively charged PS, exceeding 99%, while the biochars created at 350 °C and 550 °C exhibited lower adsorption efficiencies of less than 39% and 24% respectively (Ganie et al., 2021). Thus, the existence of functional groups on biochar contributes to strong bond energies through their ability to form hydrogen bonds, which enhances their resistance to separation. Improving the functionalization of biocharnot only boosts its adsorption capacity but also facilitates material recovery after use. A study by Babalar *et al* demonstrated this enhancement by creating a magnetic biochar–zeolite composite that was coated with various polymers (Babalar et al., 2024).

Molecules containing non-polar groups, such as C-H bonds, create mutual repulsion among water molecules, resulting in hydrophobic interactions (Xie et al., 2020). This mechanism is similarly observed in the adsorption processes of MPs onto biochar. Prior studies have

investigated how hydrophobic iron nanoparticles, modified with hexadecyltrimethoxysilane, affect the removal of MPs from environmental water samples, showing effective removal primarily facilitated by hydrophobic interactions (Grbic et al., 2019). A significant advancement was made by Tang et al., who synthesized magnetic carbon nanotubes (M–CNTs) as effective adsorbents for the removal of various MPs, including PE, PET, and PA from aqueous solutions. The success of magnetic carbon nanotubes in adsorbing MPs was largely due to strong hydrophobic interactions (Tang et al., 2021). Furthermore, hydrophobic interactions were found to be particularly influential in the adsorption of PS-MPs onto fresh corncob biochar (Magid et al., 2021).

Pore filling refers to the adsorption of organic contaminants on the surface of biochar, which possesses mesopores (ranging from 2–50 nm) and micropores (<2 nm). The effectiveness of the pore-filling mechanism is determined by the properties and classification of the biochar, in addition to the polarity of the organic contaminants (Ambaye et al., 2021). The significant presence of pores on biochar, coupled with its huge specific surface area, determines the importance of the pore-filling mechanism in the adsorption of organic pollutants. Larger organic molecules are less likely to be adsorbed due to a size exclusion effect. Research shows that the porous structure of biochar enhances microbial degradation of organic pollutants. These can be listed as follows:

(a) Pollutants that are organic enter the porous structure of the biochar, become less accessible to microorganisms, and cannot be directly used by them, thereby substantially reducing the microbial degradation rate of these pollutants (Mukherjee et al., 2022). The accessibility of organic pollutants trapped within the pores of biochar to microbial degradation is diminished due to several factors, including physical entrapment, strong sorptive interactions (such as hydrophobic and π-π interactions), and decreased bioavailability, all of which contribute to the slowing of degradation processes (Li et al., 2015).

(b) The porous structure provides a suitable habitat for microorganisms such as algae, bacteria, and fungi, increasing their abundance and activity, and potentially altering the composition or structure of the microbial community under pollutant stress (Li et al., 2015). Furthermore, the presence of partially degradable carbon and nitrogen compounds on the surface of the biochar enhances its modification with microbes (Steinbeiss et al., 2009).The porous structure of biochar

allows for better water and nutrient retention, making it an ideal habitat for microbial growth (Khan et al., 2020). This niche also provides a shielded setting for developing distinct microbial groups, thus fostering the breakdown of organic contaminants (Dong et al., 2023).

Machine learning and artificial intelligence (AI) have also emerged as powerful approaches to enhance the identification of MPs, predict biochar properties and adsorption capacities, reveal underlying mechanisms, and guide the design of engineered biochars (Yan et al., 2025). Using descriptors such as biomass characteristics, initial concentrations, and adsorption conditions, machine learning models can enhance mechanistic understanding and optimize biochar performance (Wei et al., 2024). AI-driven investigations have recently been employed to assess biochar-mediated lead immobilization in contaminated agricultural soils, suggesting that similar approaches could be applied to enhance MP remediation (Cho et al., 2024). While numerous studies have focused on elucidating the mechanisms of MPs removal with biochar, further investigation is crucial to explore the complexities of various interactions. This should encompass aspects such as surface modifications of biochar, variations in particle sizes, alternative MPs beyond extensively studied MPs like PS and PE, and relevant environmental conditions.

Adsorption of MPs onto biochar offers a sustainable and efficient remediation pathway, strongly influenced by feedstock characteristics, pyrolysis conditions, and surface modification methods. Enhanced functionalities, coupled with increased surface area and porosity, improve active site availability, achieving removal efficiencies greater than 99% for various MPs. Dominant interaction mechanisms include π-π interactions, electrostatic attractions, hydrogen bonding, and hydrophobic interactionsas confirmed by detailed characterization analyses. However, real-world performance and application remain limited by environmental complexities, highlighting the need for advanced modifications and the emerging scope of AI-assisted modeling to predict adsorption behavior, optimize selectivity, and enhance large-scale applicability.

4.0 Biochar and the circular economy: redefining waste for a cleaner future

As the global population surges, waste generation, particularly organic waste, has escalated drastically. It is imperative that we harness resources effectively and devise strategic solutions

for effective waste management. Since early times, landfilling has been the predominant waste disposal method, particularly for municipal solid waste; however, the finite availability of suitable land is causing these sites to reach capacity at an alarming rate. Landfilling of waste also raises significant concerns regarding the potential leaching of contaminants into soil and water systems, which could ultimately penetrate the food chain. Directly depositing waste into landfills without adequate recycling results in severe environmental challenges, including escalating emissions of harmful or toxic gases such as carbon dioxide (CO_2), carbon monoxide (CO), particulate matter, and sulfur dioxide (SO_2). Biomass and organic waste are effective resources for conversion into valuable products like biochar, syngas, and bio-oil through the pyrolysis process. The transformation of organic waste into biochar is particularly notable for its capacity to mitigate atmospheric CO_2 levels.

The framework of the circular economy as it pertains to the production and utilization of biochar is effectively depicted in Figure 9. Biochar derived from various wastematerials, particularly sludge from wastewater treatment facilities, shows excellent potential in adsorbing various emerging contaminants like Pharmaceuticals from soil and water. Its application significantly enhances soil quality, promoting sustainable agricultural practices and environmental remediation. Bamboo waste-sludge biochar achieved a 95% removal rate for Ciprofloxacin (CIP) at 10 $mg.L^{-1}$, with a maximum adsorption capacity of 62.48 $mg.g^{-1}$ (Li et al., 2020). Pharmaceutical sludge-derived biochar reached 94.69 $mg.g^{-1}$for Tetracycline at 600 °C (Liu et al., 2020), while municipal sewage sludge biochar produced by fast co-pyrolysis adsorbed Nickel (II) effectively (Yang et al., 2019). After adequate purification, this treated water can be repurposed and reused for agricultural purposes.In the process of biochar production, approximately 50% of the initial carbon content is retained, and it is estimated that the annual application of biochar can potentially offset up to 12% of global CO_2 emissions resulting from land use (Zhu et al., 2022). Additionally, an imperative study found that biochar application increased soil CH_4 absorption while decreasing N_2O emission peaks, N_2O emission factors, and cumulative emissions. Although excessive application (22.5 t ha^{-1}) increased CO_2 cumulative emissions, biochar decreased cumulative soil CO_2 emissions (Ren et al., 2025). Research has highlighted biochar's efficacy in sequestering essential nutrients like nitrogen (N) and phosphorus (P), thereby enhancing its role in soil amendment and improvement (Janu et al., 2021). This application improves soil productivity and assists in carbon sequestration,

functioning as a carbon sink. A separate study demonstrates that the application of sugarcane bagasse biochar at suitable rates notably decreases methane (CH_4) emissions in soil samples. In contrast, the incorporation of PS into paddy soil samples leads to an increase in CH_4 emissions (Rassaei, 2023). Further, introducing biochar into soil has been found to reduce nitrous oxide (N_2O) emissions and improve CH_4 uptake, consequently lowering overall greenhouse gas emissions. Moreover, biochar enhances the sorption capabilities of soils toward specific pollutants (Chan et al., 2007).

Ongoing research continues to investigate these pathways, and in alignment with circular economy principles, the syngas and bio-oils generated through pyrolysis can be valorized for decentralized electricity production and as renewable energy inputs across a range of industrial and rural applications, including domestic heating, clean cooking, and off-grid lighting solutions. This energy can also be effectively utilized to power the pyrolysis reactor, further reinforcing the concept of a circular economy as highlighted in Figure 9.These findings underscore the potential of biochar as a viable, enduring, and environmentally sustainable strategy for mitigating climate change.

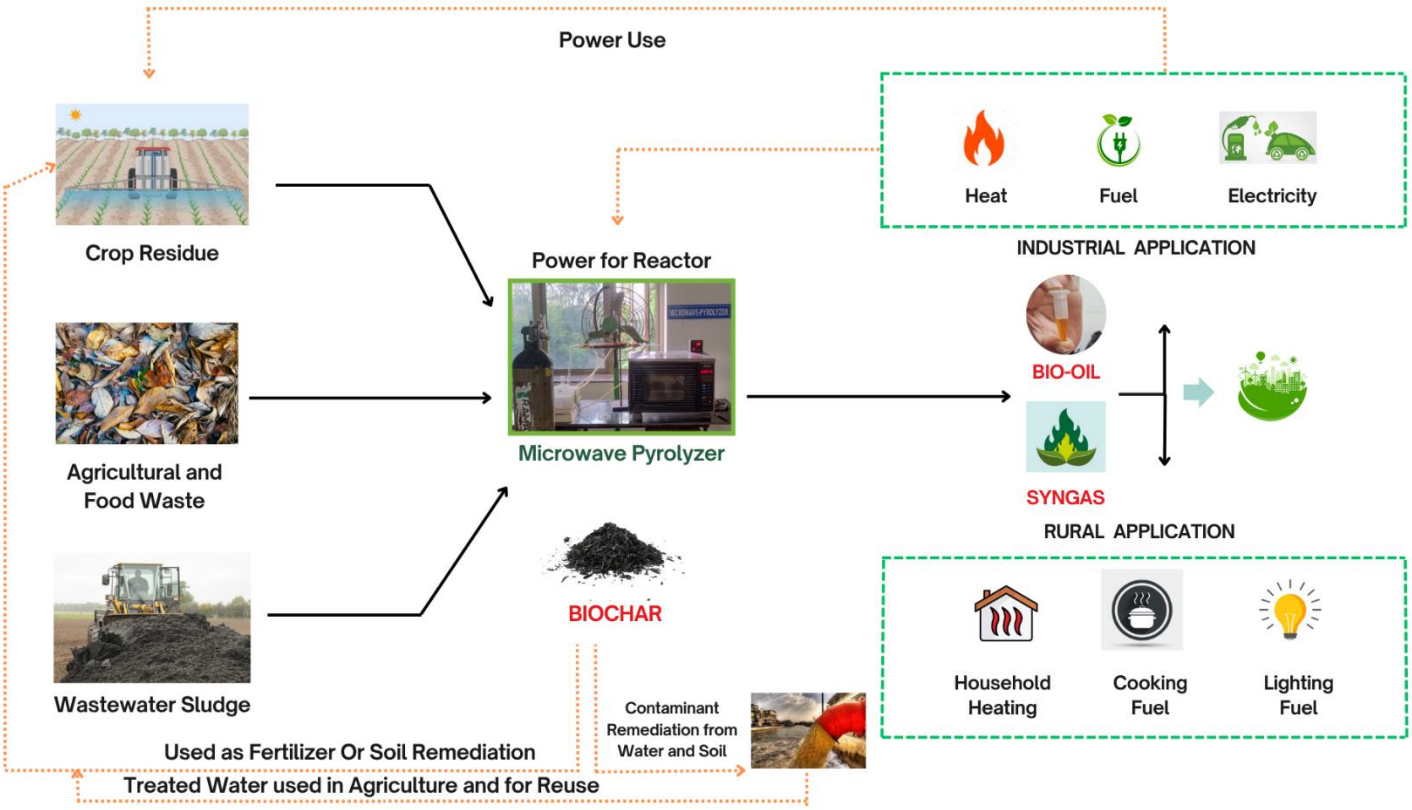


Figure 9: Framework for biochar production and utilization; from trash to treasure.

Biochar transforms organic waste into a valuable resource, enhancing soil quality, reducing greenhouse gas emissions, and enabling contaminant removal.While there are some potential limitations to biochar application, which have been discussed in the next section, the benefits could outweigh the drawbacks if implemented strategically. The conversion of biomass into biochar, bio-oil, and syngas represents a pivotal strategy for achieving net-zero emissions and advancing climate change mitigation efforts in alignment with the Sustainable Development Goals (SDGs) established by the United Nations.

5.0 Limitations and potential negative impacts of biochar applications

Biochar is an intriguing area of research for scientists worldwide, particularly for contaminant remediation and mitigation. The increasing utilization and research on biochar is primarily driven by its economic efficiency and the availability of suitable feedstock. Despite its advantages, the growing interest in biochar has revealed several likely drawbacks and limitations, which can be categorized into four primary concerns.

- The first concern involves the effective regeneration of spent biochar. The desorption of pollutants for safe treatment, recycling, and disposal raises significant issues. Improper management of this process can lead to further contamination. Specific contaminants of concern include heavy metals (such as Pb, Cd, and As), persistent organic pollutants (like PAHs and dioxins), and emerging contaminants (including pharmaceuticals and MPs). Though thermal regeneration is commonly used due to its lower energy demands, it risks emitting volatile organic compounds and particulate matter. Alternative methods, such as its regeneration for multiple cycles and microbial degradation, are being researched to reduce these emissions, but further optimization is required for large-scale use.

- The second concern addresses environmental risks. The possibilityof secondary pollution has led to increased scrutiny of biochar applications, especially with the recent advancements in modified biochar that exacerbate these worries.For instance, acidic or alkaline modifications can leach residual chemicals, and metal-impregnated biochar may release toxic ions. While nanoscale modifications enhance adsorption, they raise concerns

about nanoparticle toxicity and long-term ecological effects. Research suggests that surface passivation and coating techniques could help mitigate these risks, but standardized guidelines for safe practices are still lacking. Furthermore, the effective separation of treated biochar from aquatic environments remains an urgent issue that necessitates immediate attention.

- The third concern pertains to optimizing the adsorption capacity and associated costs of biochar. Various techniques, including adjustments to the production process, biochar modifications, or integration with other treatment methods, are employed to enhance adsorption capacity. Chemical activation and hybrid composites improve performance but often involve high costs and energy demands. Viable low-cost alternatives, such as waste-derived phosphoric acid and mechanochemical synthesis, offer a balance of efficiency and affordability. Life Cycle Assessment (LCA) studies reveal that the environmental impacts of these methods differ substantially, highlighting the need for optimization approaches tailored to specific cases (Mishra et al., 2023).

- The fourth challenge lies in understanding the adsorption mechanisms of biochar for the remediation of MPs. Key factors influencing the removal efficiency include pore structure, surface charge, and hydrophobicity, with competitive adsorption in mixed-pollutant systems often reducing effectiveness. Nanoscale MPs present additional complexity due to weak van der Waals forces. Research suggests that magnetic or polymer-modified biochar may improve selectivity for MPs, although their long-term stability is not yet confirmed. Recent research indicates that the adsorption of PS, PE, and PMMA is influenced by electrostatic repulsion, hydrogen bonding, and π-π interactions (particularly for PS). The negative charges of biochar and MPs can hinder adsorption, making the understanding of these interactions crucial for developing effective adsorbents for MP remediation (Zhang et al., 2025a).

Other limitations include the non-specificity and competitive interactions that occur when multiple contaminants are present.Research indicates contaminants such as tetracycline, ciprofloxacin (Zhao et al., 2024), and humic acids may lead to competitive adsorption by occupying the active sites on the surface of biochar that would otherwise be available for MPs (Jiang & Hu, 2024). Moreover, the presence of MPs diminished the metal adsorption efficiency

of biochar, with reductions ranging from 0.72% to 50.35% for Cd, 1.17% to 30.43% for Ni, and 5.78% to 47.88% for Cu, respectively (Meng et al., 2024). When biochar is incorporated into biological treatment systems, it can act as a substrate for microbial colonization, which may lead to biofouling, clogging, and decreased adsorption efficiency. Operational risks related to the release of airborne fine biochar particles during both production and application in the field raise important health concerns for workers. Existing mitigation strategies predominantly utilize engineering controls, such as enclosed reactors and wetting agents, complemented by personal protective equipment (PPE). Nonetheless, innovative developments in biochar pelletization and encapsulation present promising strategies to significantly reduce dust-related risks.

To address these challenges, focused research is critically needed in several key domains;

1. Development of advanced regeneration techniques that effectively eliminate the risk of secondary pollution.

2. Formulation of safer modification protocols designed to reduce leaching and toxicity.

3. Implementation of cost-effective production methods that are substantiated by LCA.

4. Conducting mechanistic studies on the adsorption of multiple pollutants, particularly concerning interactions with MPs.

5. Establishment of standardized disposal protocols for contaminated biochar, alongside strategies for the possible reuse of spent biochar in construction applications. The market for biochar applications in construction is experiencing gradual growth, indicating significant scope for expansion.

Advances in regeneration, safe modification, cost-effective production, and mechanistic understanding, along with standardized reuse strategies, are critical to harness biochar’s full potential as a sustainable and scalable remediation tool.By prioritizing these gaps, the scientific community can unlock biochar’s full potential while ensuring environmental and operational safety.

6.0 Perspectives

Futuristic research fields include exploring the synergistic integration of microbial horizontal gene transfer (HGT) and biochar-based systems for enhanced MP remediation. This innovative approach leverages the adsorption capabilities of biochar in combination with its potential for microbial immobilization. By promoting genetic exchange through HGT, researchers aim to optimize microbial consortia for more efficient biodegradation of MPs. This strategy offers a sustainable and impactful solution to address MP pollution in both wastewater and soil environments. A recent investigation indicated that biochar can potentially impede the conjugative transfer of antibiotic resistance genes (ARGs) primarily by limiting energy availability and affecting cell membrane permeability (Wu et al., 2022). Studies have demonstrated that the use of biochar in soils that are simultaneously contaminated with biodegradable MPs and copper can help minimize the dissemination of ARGs (Wang et al., 2025). Novel research indicates that biochar-based solutions, such as phosphorite magnetic biochar for treating cadmium-contaminated paddy soils (Chen et al., 2025) and the use of biochar to reduce plasmid-mediated antibiotic resistance gene transfer in earthworm ecological filters, offers innovative strategies for mitigating heavy metal toxicity and controlling antimicrobial resistance in rural sewage and agricultural systems (Zhao et al., 2025). Promoting HGT among microbial consortia can facilitate the development of robust communities that can degrade a broader range of MPs. Biochar is emerging as a powerful tool against emerging contaminants, extending its utility beyond MPs to include a broad spectrum of pollutants. Recent research highlights its effectiveness against Pharmaceuticals and Personal Care Products (PPCPs), Per- and Polyfluoroalkyl Substances (PFAS), and Endocrine Disrupting Compounds (EDCs). This versatility positions biochar as a key player in innovative remediation strategies for complex environmental challenges.

These findings emphasize the growing relevance of biochar- its modified forms and derivatives from plastic waste as effective and versatile tools for MP remediation. Beyond its technical efficacy, the widespread adoption of biochar-based strategies offers profound environmental and social benefits. These include the reduction of plastic waste through upcycling into functional materials, enhancement of soil health and water retention in agricultural settings, and significant improvements in water quality across urban and rural systems. By supporting circular economy principles and advancing climate-resilient infrastructure, biochar has the capacity to redefine pollution control at the nexus of waste management, environmental restoration, and public

health. A recent study by Biochar Europe, titled “Biochar as the key to a Climate-Neutral, Competitive and Resilient European Economy”, underscores the accelerating integration of biochar across industrial and research domains within Europe (Hauser & Europe, 2025). The report highlights not only the expanding applications and transformative potential of biochar but also emphasizes the pivotal influence of policy frameworks in enabling its widespread adoption and impact. As research continues to uncover innovative convergences with microbial ecology, photocatalysis, and renewable energy, biochar is poised not only to address the complex challenge of MPs but also to catalyze a broader shift toward sustainable and integrative environmental solutions.

Current research investigations predominantly study PS and PE-MPs with uniform morphology, which do not reflect the heterogeneity of environmental MPs that vary in size, shape, density, surface chemistry, and complex additive composition. Future research directions emphasize the inclusion of a broader polymer spectrum, including PET, PVC, and PA, to enhance environmental relevance (Mota et al., 2025; Olubusoye et al., 2024). Despite substantial advances in laboratory-scale investigations,the application of biochar for MP removal in pilot-scale and real-world wastewater contexts remains limited.Although a few studies have explored the pyrolysis of biosolids in novel fluidized bed heat exchanger reactors, examining aspects such as pilot plant trials, biochar characteristics, gas emissions, and PFAS fate, the specific implications for MP mitigation in such systems are largely absent (Hakeem et al., 2025). Conventional sludge treatment processes are largely ineffective in eliminating MPs from sewage sludge and often contribute to the generation of smaller particles with modified surface morphology, thereby enhancing the potential for co-contaminant adsorption (Khan et al., 2022b; Vinay et al., 2023). The complex interactions of MPs with co-contaminants such as PFAS in real aqueous environments, and the performance of biochar therein, require more detailed and mechanistic investigation (Xie et al., 2025).

Future research directions can emphasize integrative approaches that combine laboratory precision with field-scale relevance.The development of imperative hybrid analytical techniques, including the coupling of Raman spectroscopy with mass spectrometry or electrochemical analysis, can significantly improve the sensitivity and comprehensiveness of MPs and NPs detection (Farale et al., 2025). In addition, the design of portable, real-time analytical platforms for in situ monitoring can reduce dependence on complex laboratory analyses. Progress in

computational modeling, incorporating machine learning, AI and advanced experimental design methodologies, holds immense promise for MP detection as well as optimizing biochar properties and performance in realistic environmental matrices for effective MP remediation (Hossain & Engineering, 2025; Jin et al., 2024). Thus, research highlights the growing promise of biochar, particularly its modified forms, as an effective tool for MP remediation. Beyond technical performance, biochar-based strategies offer environmental and social benefits, including plastic waste reduction, improved soil health, and enhanced water quality. By aligning with circular economy principles and supporting sustainable infrastructure, biochar contributes meaningfully to pollution control and ecosystem restoration. This potential, supported by significant technical advancements, economic viability, strong governmental support, and growing societal awareness, positions biochar as a valuable component in future environmental management strategies.

7.0 Conclusion

Biochar and its modified forms have emerged as highly effective methods for addressing MP contamination. Future investigations should prioritize the integration of biochar with advanced treatment technologies to optimize its effectiveness in practical wastewater treatment applications. Biochar has emerged as a promising support for solar-driven photocatalysis due to its diverse surface functional groups and unique structural characteristics, which impart notable redox activity that allows its engagement in electron transfer processes. Renewable energy sources such as solar radiation, in conjunction with innovative treatment methods like photocatalysis could advance sustainability in this regard.

It is imperative to conduct pilot-scale experiments to verify the performance of biochar in both industrial and municipal wastewater systems. Transitioning from laboratory to real-world applications encounters several hurdles: (1) competitive adsorption in complex wastewater environments, (2) biochar fouling by various organic and inorganic contaminants, (3) hydraulic inefficiencies such as preferential flow and MP breakthrough in column systems, and (4) challenges in post-treatment separation of biochar-MP aggregates (Hanif et al., 2025; Yang et al., 2024).

In a recent study conducted, the degradation performance of emerging contaminants by the Fe–biochar/peroxymonosulfate/sunlight system in tap water was enhanced in the presence of MPs, likely attributed to the release of dissolved organic matter from MPs that facilitated photoactivation or direct adsorption processes.

There is also scope for exploring the conversion of plastic waste into biochar for MP remediation, which could strengthen the principle of circular economy. The co-pyrolysis of pristine biochar with MPs such as PP, PVC, PS, and PLA is an effective strategy to enhance the properties of pristine biochar. The resulting co-pyrolyzed biochar exhibited superior catalytic activity compared to pure algal-derived biochar (Qin et al., 2024), suggesting their ability to function both as adsorbents for MP removal and as catalysts for MP degradation. Machine learning models and AI can optimize biochar design, enhance MP remediation, and provide valuable mechanistic insights. Thus, modified biochar, combined with advanced treatment strategies, presents a sustainable, scalable approach for MP remediation, supporting circular economy goals and enhancing environmental restoration.

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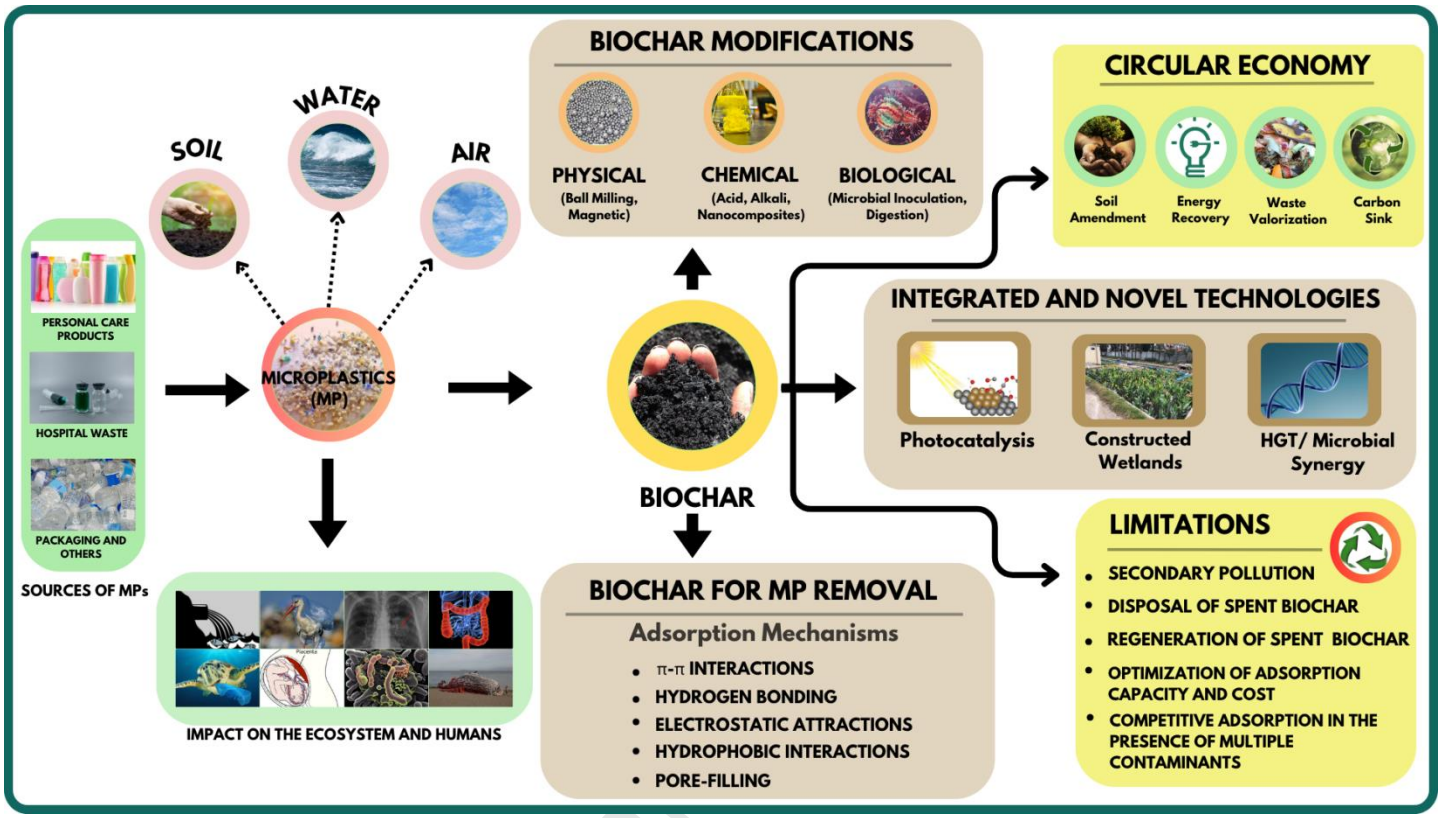
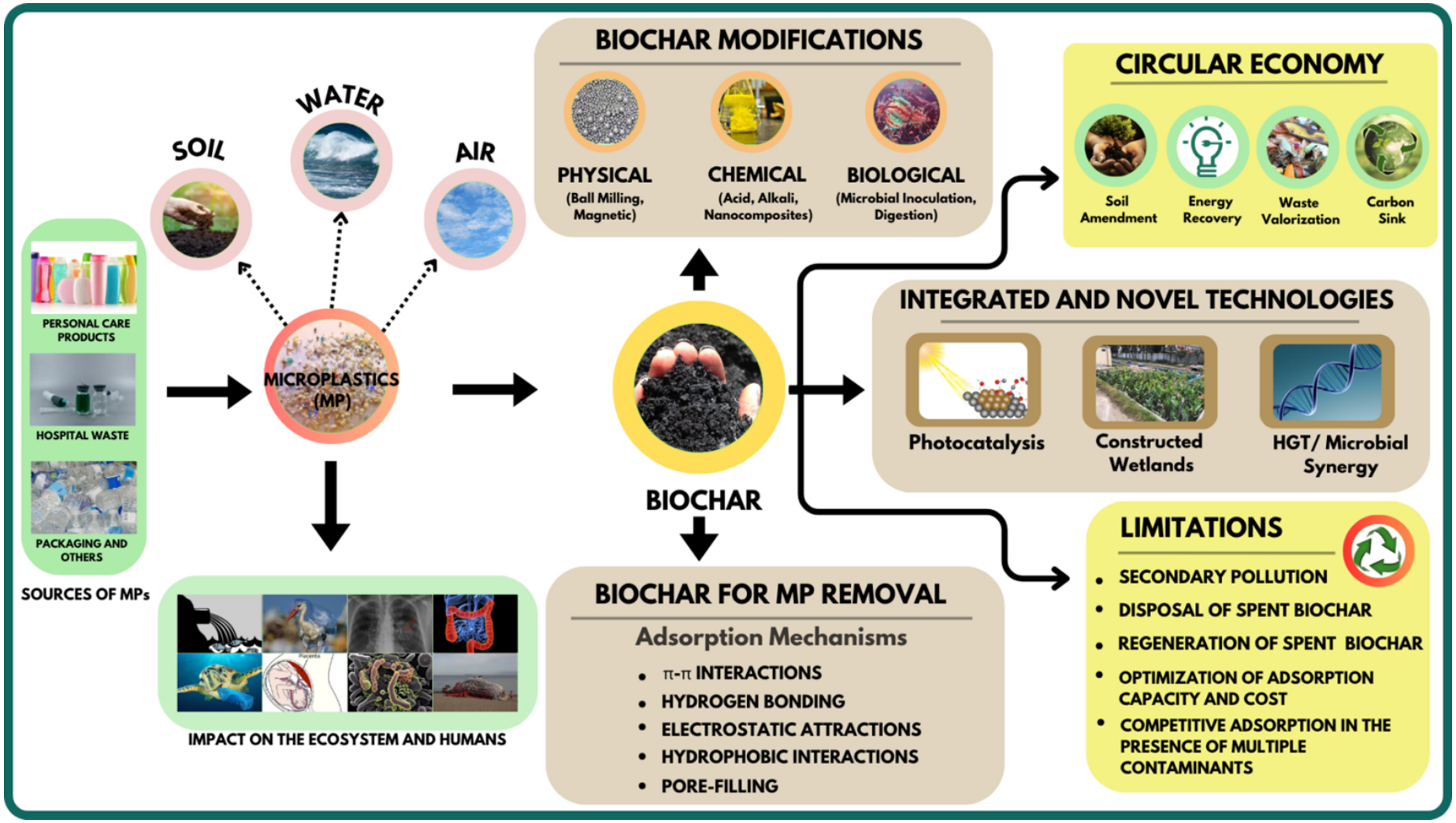
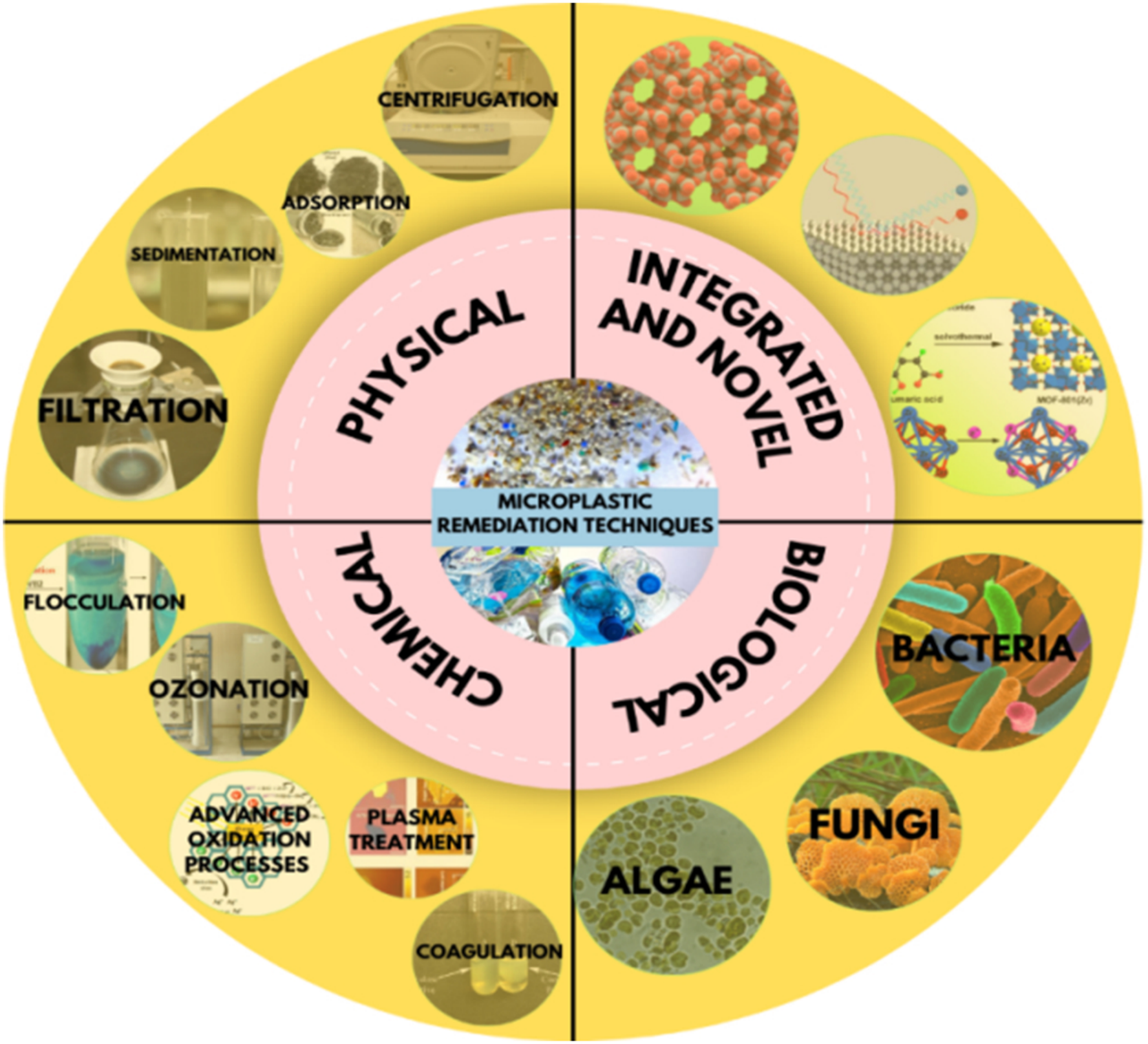
Graphical Abstract





Graphics Abstract


MICROPLASTIC REMEDIATION TECHNIQUES
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FILTRATION
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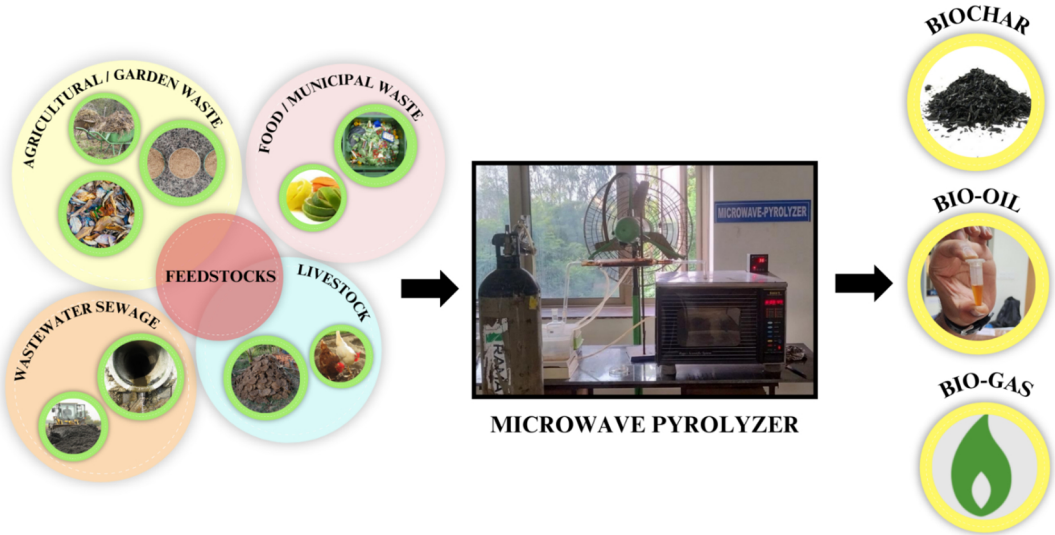
PLASMA TREATMENT
COAGULATION
BACTERIA
FUNGI
ALGAE

Figure 1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FOOD / MUNICIPAL WASTE
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LIVESTOCK
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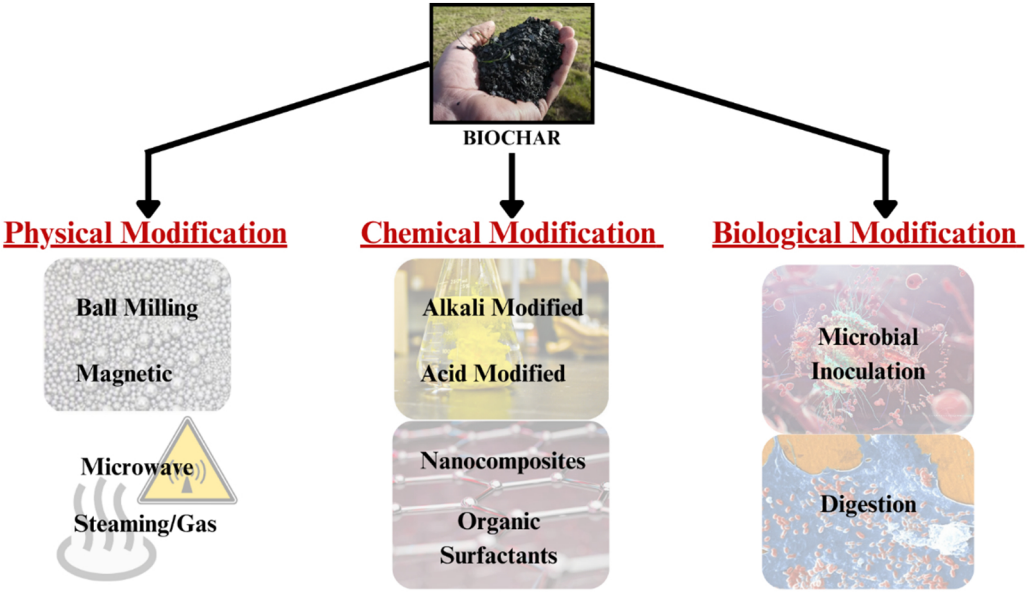
MICROWAVE PYROLYZER
BIOCHAR
BIO-OIL
BIO-GAS

Figure 2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Magnetic
Microwave
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Acid Modified
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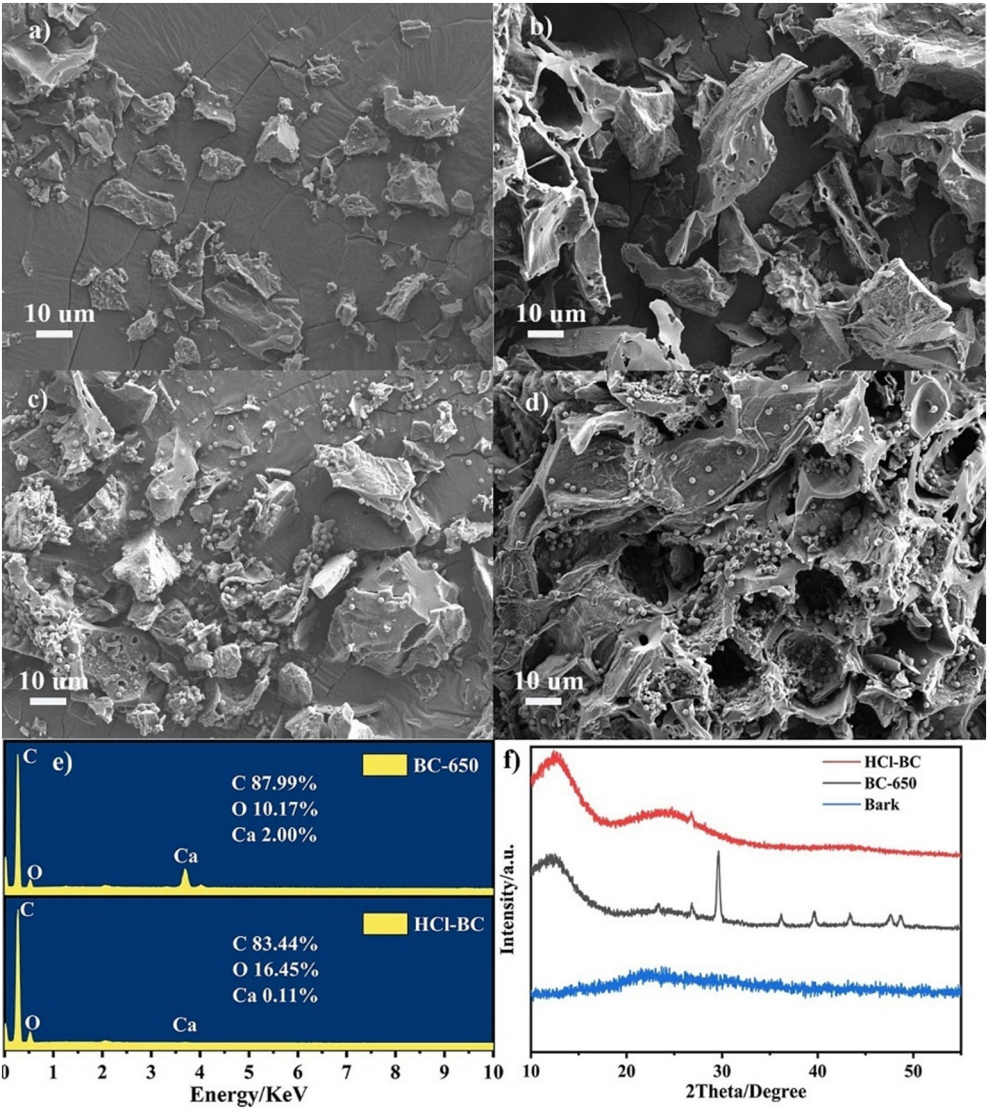
Surfactants
Biological Modification
Microbial
Inoculation
Digestion

Figure 3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Ca 2.00%
HCl-BC
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Ca 0.11%
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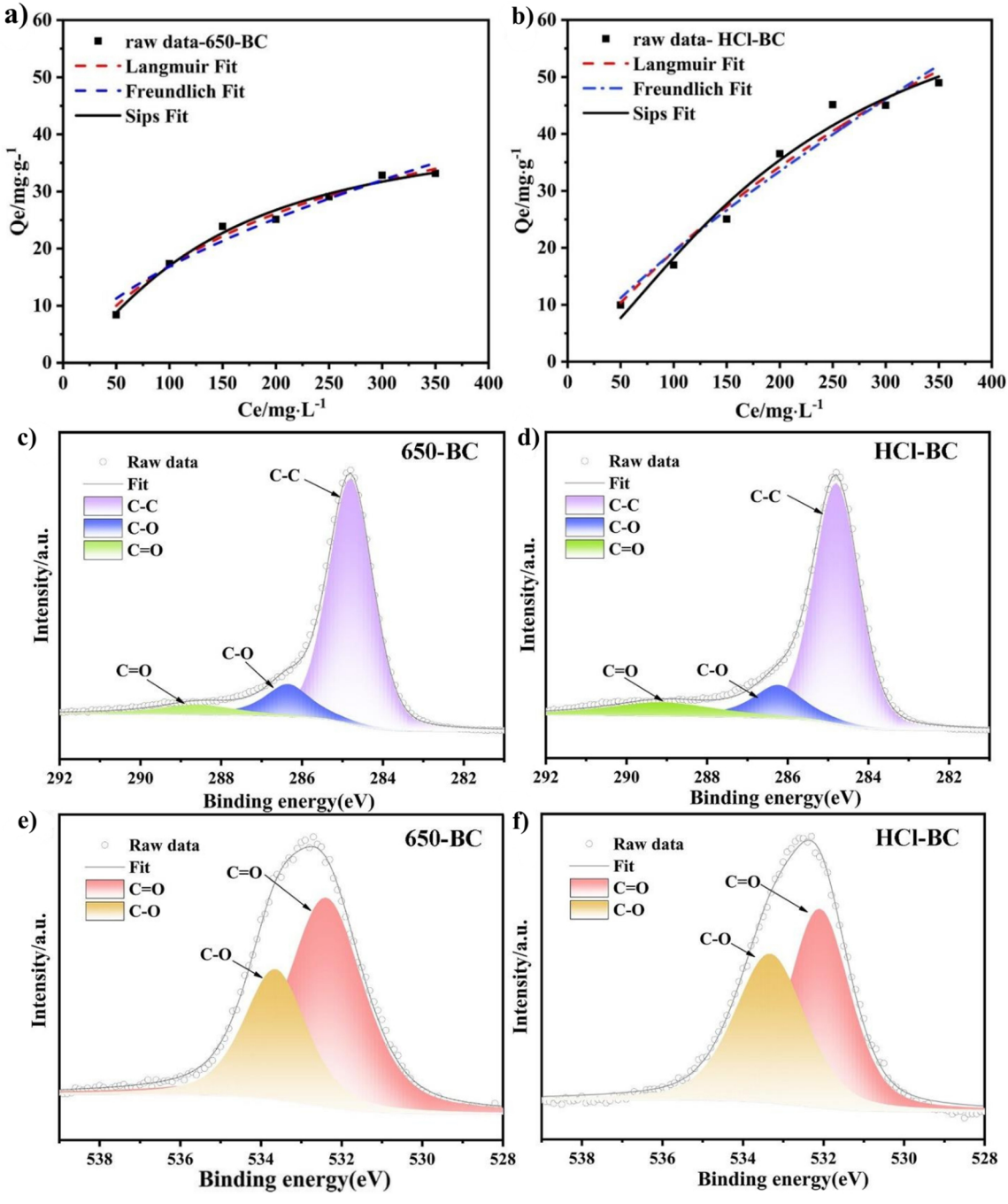
Figure 4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b)
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Freundlich Fit
Sips Fit
Qe/mg·g-1
Ce/mg·L-1
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650-BC
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C-C
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Intensity/a.u.
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Binding energy(eV)

Figure 5

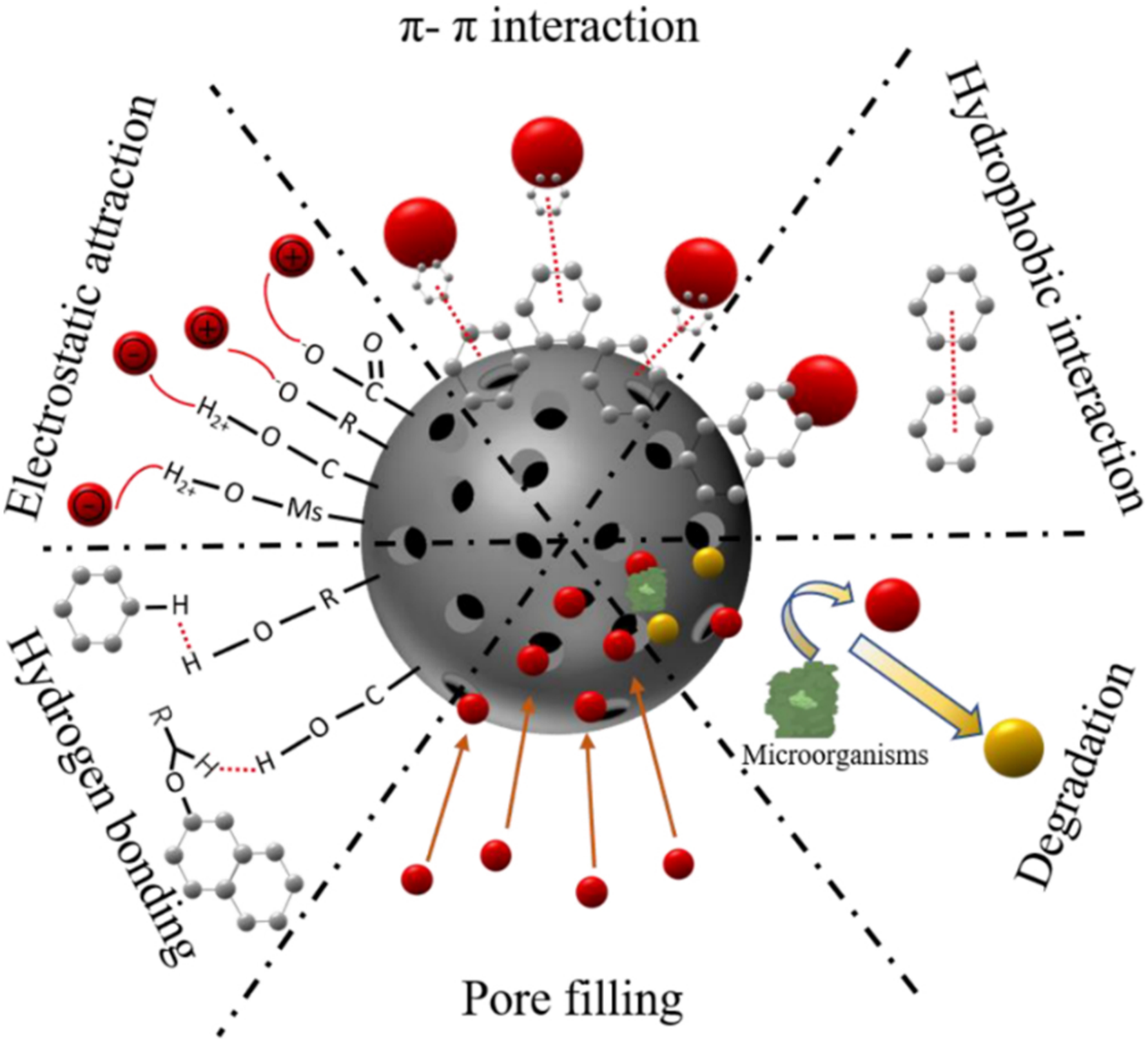
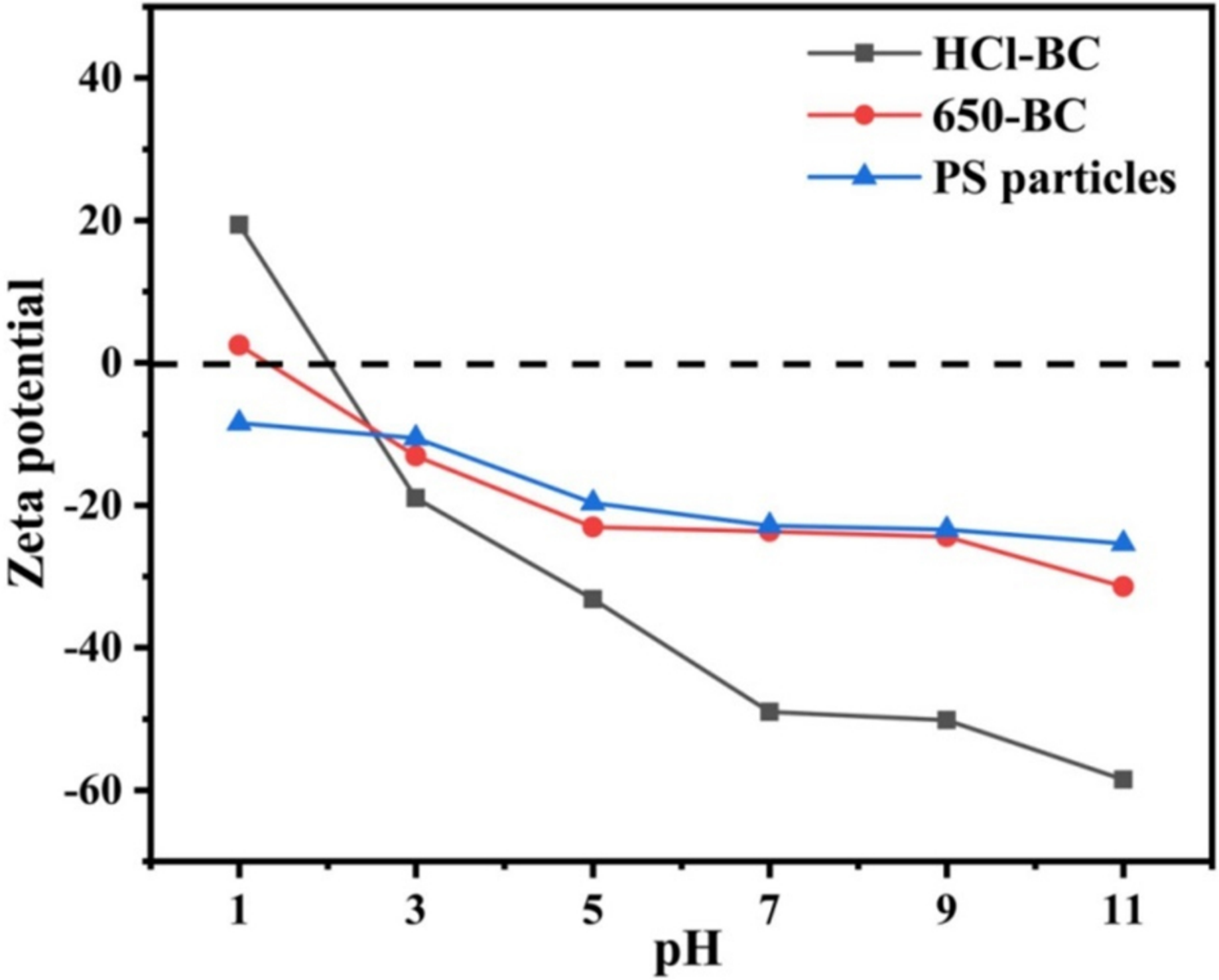

π- π interaction
Electrostatic attraction
Hydrophobic interaction
Hydrogen bonding
Pore filling
Degradation
Microorganisms

Figure 6


HCl-BC
650-BC
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-20
-40
-60
Zeta potential
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11
pH

Figure 7

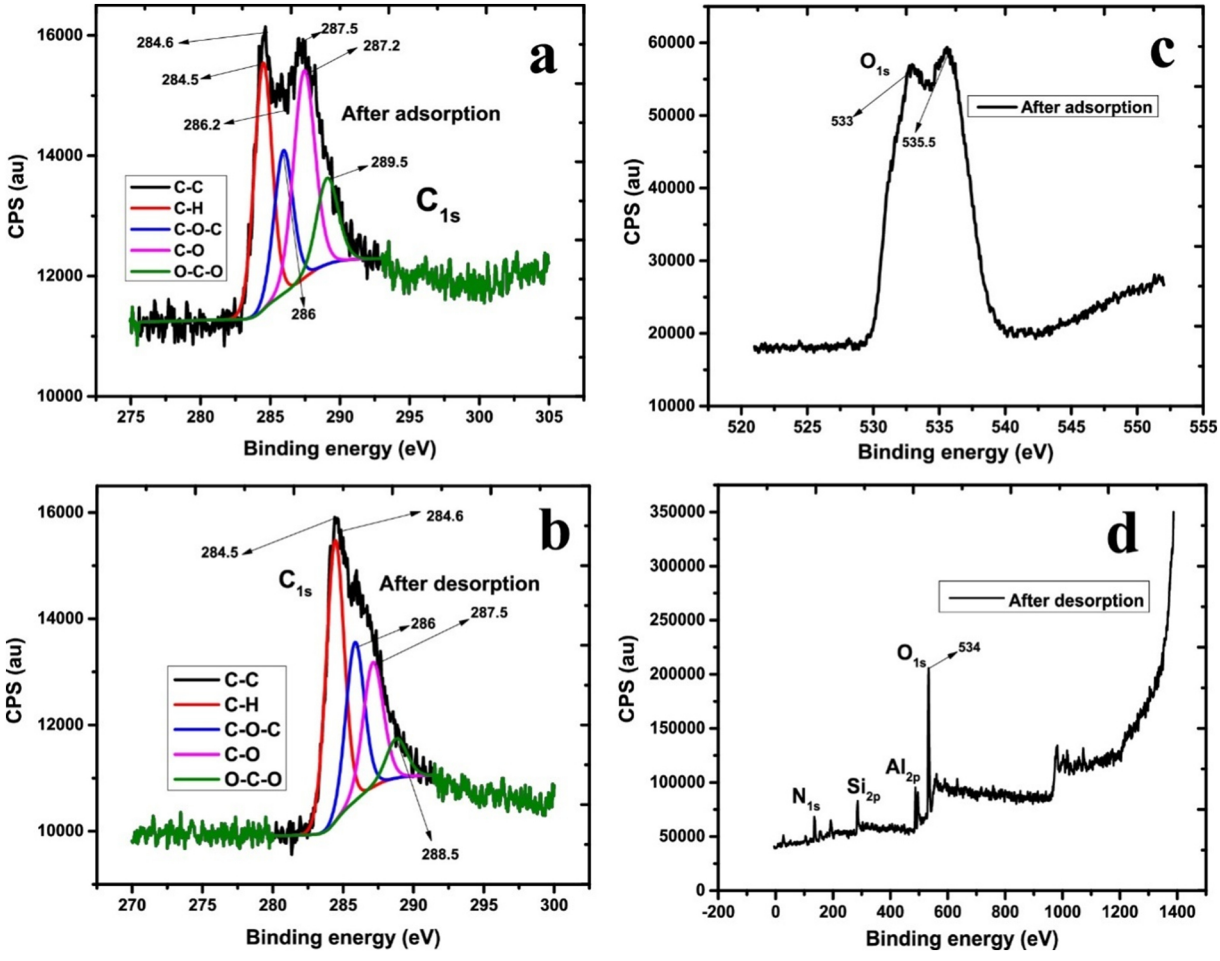
a
284.6
284.5
287.5
287.2
286.2
After adsorption
289.5
C1s
C-C
C-H
C-O-C
C-O
O-C-O
286
CPS (au)
Binding energy (eV)
c
O1s
533
535.5
After adsorption
CPS (au)
Binding energy (eV)
b
284.5
284.6
C1s
After desorption
286
287.5
C-C
C-H
C-O-C
C-O
O-C-O
288.5
CPS (au)
Binding energy (eV)
d
After desorption
O1s
534
N1s
Si2p
Al2p
CPS (au)
Binding energy (eV)

Figure 8

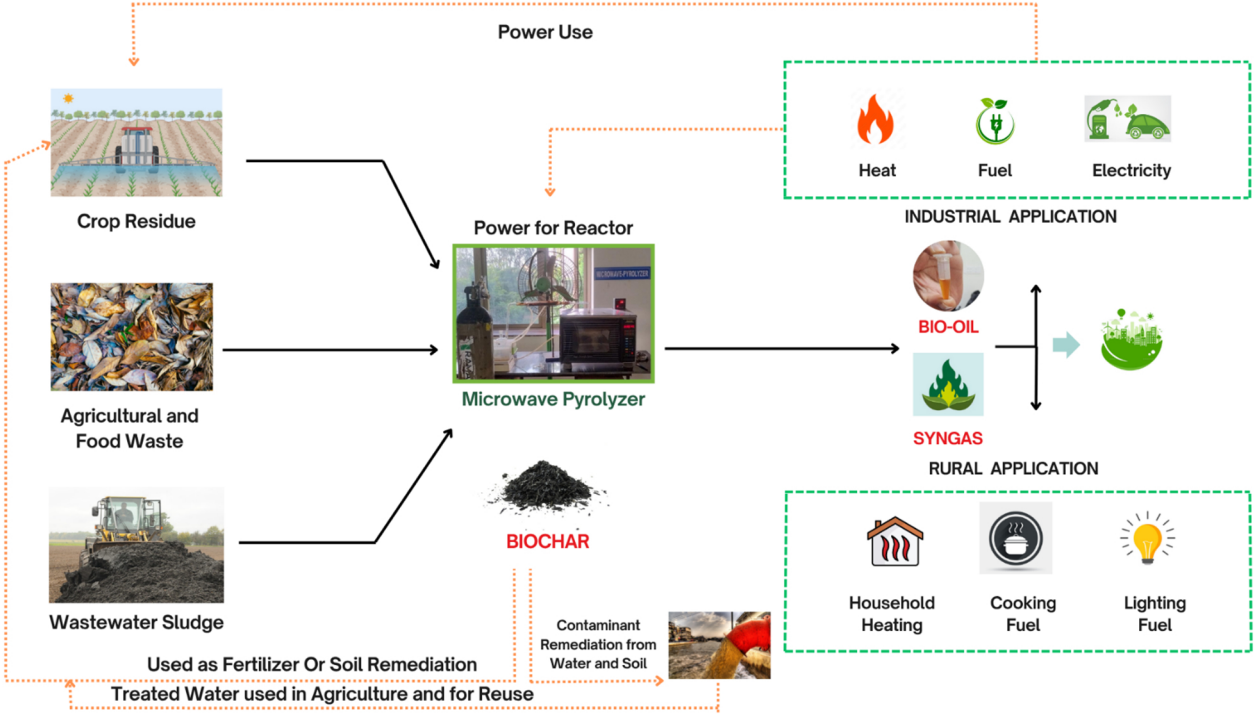
Power Use
Crop Residue
Agricultural and Food Waste
Wastewater Sludge
Power for Reactor
Microwave Pyrolyzer
BIOCHAR
Heat
Fuel
Electricity
INDUSTRIAL APPLICATION
BIO-OIL
SYNGAS
RURAL APPLICATION
Household Heating
Cooking Fuel
Lighting Fuel
Contaminant Remediation from Water and Soil
Used as Fertilizer Or Soil Remediation
Treated Water used in Agriculture and for Reuse

Figure 9