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Biochar

REVIEW

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Biochar-driven rhizoremediation of soil contaminated with organic pollutants: engineered solutions, microbiome enrichment, and bioeconomic benefits for ecosystem restoration

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Abstract

Soil contamination with organic pollutants is a growing environmental concern, with the FAO reporting that 80% of agricultural soils contain such residues. Industrial chemical production has doubled to 2.3 billion tonnes and is projected to increase by 85% by 2030, exacerbating the issue. Key pollutants include pesticides, pharmaceuticals, antimicrobials, and plastic residues, contributing to a 15–20% loss in agricultural productivity. In this context, rhizosphere-mediated remediation has gained significant attention for its potential to degrade organic contaminants. Rhizoremediation, when integrated with biochar application, not only enhances contaminant degradation but also supports plant and microbial growth due to biochar's nutritive properties and its role in improving contaminant bioavailability. This review explores the synergistic interactions between plant–microbe systems and the role of biochar in accelerating the degradation of major organic contaminants, including crude oil, pesticides, polycyclic aromatic hydrocarbons (PAHs), antibiotics, and organic dyes, aligning with circular bioeconomy principles. Additionally, meta-omics approaches such as metagenomics, transcriptomics, and metabolomics provide insights into active microbial communities involved in the rhizoremediation-biochar process. The efficiency of pollutant sorption and desorption is influenced by biochar's chemical structure, composition, porosity, surface area, pH, elemental ratios, and functional groups. Therefore, this review also highlights the potential of engineered biochar for enhanced rhizoremediation while addressing challenges associated with its application, emphasizing the need for optimization strategies to mitigate any negative impacts. Furthermore, the exponential growth of the biochar market, valued at USD 2.05 billion in 2023, presents a promising opportunity for both global economic expansion and ecosystem restoration, underscoring the significance of biochar in sustainable environmental management.

Highlights

- Biochar application with rhizoremediation is a novel strategy for organic contamination remediation.
- Meta-omics technologies reveal degradation insights in rhizoremediation with biochar amendments.
- Bioengineered biochar improves eco-restoration strategies and promotes plant growth.

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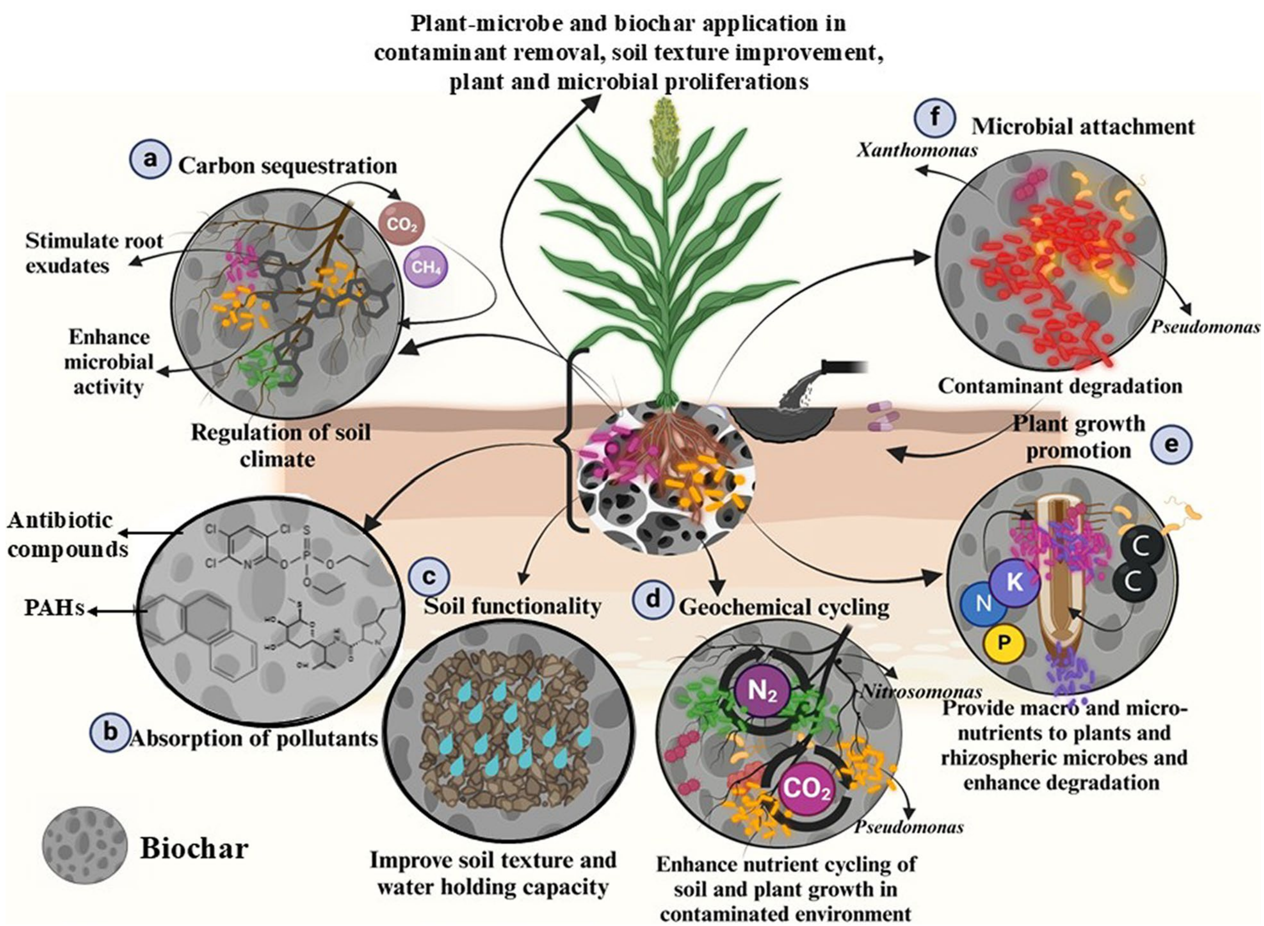
- The global biochar market can boost the circular economy and support sustainable restoration.

Keywords Organic contamination, Rhizoremediation, Catalysts, Meta-omics, Biochar engineering

Graphical Abstract



1 Introduction

In 2015, the United Nations established the seventeen Sustainable Development Goals (SDGs) to tackle worldwide issues related to environmental conservation, human health consequences, poverty eradication, and the promotion of peace and economic stability (Khargonekar and Samad 2024). Despite being explicitly addressed in objectives 3.9 and 12.4, soil pollution has the potential to impede the achievement of other SDGs such as "clean water and sanitation" (SDG 6) and "zero hunger" (SDG 2) (Zhou et al. 2021; Pingali and Plavšić, 2022a, b), highlighting its consequences and the urgent need for mitigation strategies (Scarborough et al. 2023).

One-third of global soil is polluted and dealing with global environmental issue due to organic contaminants (Gautam et al. 2023). Environmental contaminants are responsible for around 13 million fatalities annually throughout the globe (Awewomom et al. 2024). Approximately 50% of Canada's federal soil has been identified as contaminated with various types of contaminants, including phenolic compounds, PAHs, halogenated compounds, crude oil, petroleum products, pesticides, and chlorinated compounds (Miglani et al. 2022). According to a 2018 study by the FAO, the petroleum and its by-products affected the soil of more than 100,000 hectares of land in Russian Federation (NOSDRA, 2006; Matuszak, 2021). Between 2006 and 2022, Nigeria recorded a total of 4102 crude oil spillage incidents, including the accidental discharge of 253,143 barrels of oil into the lands (Adeniran et al. 2023). UNEP's report indicates a concerning increase in pesticide active ingredient usage per unit of crop land from 1990 to 2016, with a 75% increase from 1.9 kg ha^{-1} to 3.3 kg ha^{-1} (Siboni 2023a, b), contributing to the emergence of antimicrobial resistance (AMR) (Barathe et al. 2024).

Persistent organic contaminants tend to bioaccumulate and biomagnifies within the food chain, resulting in frequent human exposure through various pathways, including ingestion, inhalation, dermal absorption, and intravenous routes (Aravind et al. 2022). Soil contamination with crude oil leads to 60% food security reduction and 24% malnutrition in children due to their accumulation within the food chain (Das et al. 2024a, b). Over 600 million people worldwide are affected by PAHs, which pose significant health risks due to their mutagenic and carcinogenic properties (Das et al. 2024a, b). Table 1 shows the different health impact caused due to the xenobiotics' contamination in soil and the sources of contamination.

Techniques such as coagulation, filtration, adsorption, chemical precipitation, electrolysis, and ozonation are commonly employed for the degradation of organic contaminants. However, concerns regarding their reliability and the potential generation of toxic by-products highlight risks associated with their application (Singha and Pandey 2021). Rhizoremediation, a nature-based solution, leverages the synergistic interaction between plant roots and beneficial microbial communities to degrade environmental contaminants. The enhanced influence of plants in rhizosphere environments can improve the efficacy of this process by promoting the active microbial population capable of metabolizing and neutralizing organic contaminants (Bisht et al. 2015; Singha and Pandey 2017). Nevertheless, the effectiveness of rhizoremediation can be hindered by several challenges, including restricted microbial activity and the limited bioavailability of pollutants, which may reduce the degradation efficiency for the contaminants (Wani et al. 2023). Thus, the application of biochar may significantly contribute to the enhancement of plant growth and facilitate the bioavailability of contaminants for degradation.

The use of biochar-based materials as catalysts or catalytic supports in environmental detoxification is increasingly gaining attention. Biochar is a porous carbonaceous material, produced from various feedstocks via thermochemical and biochemical methods (Muh and Tabet 2019). The addition of biochar to the soil has a significant capacity to enhance carbon (C) sequestration due to the aromatic structure of the C in biochar (Perchikov et al. 2024). Research suggests that the global application of biochar has the potential to reduce greenhouse gas emissions by up to 12% (Yin et al. 2021). The incorporation of 20% coffee husk biochar into Brazilian Oxisols resulted in a 100% increase of the cation exchange capacity (CEC) of the soil (Ndoung et al. 2021a, b). Research has also demonstrated that biochar reduces fertilizer requirements by 60% (Nepal et al. 2023). Moreover, biochar application enhances organic chemical bioavailability in polluted soils (Kapoor and Zdarta 2024), as the application of biochar immediately stimulates soil microbiota, enhancing soil quality and health (Singh et al. 2018). Furthermore, the activation and surface functionalization of biochar using acid and alkali solutions, oxidizing agents, microbes, and chemicals to produce engineered biochar with specific adsorption characteristics plays a crucial role in eco-restorations and pollution mitigation. Recently, Munir et al. (2024) reviewed the potential applications of biochar in constructed wetlands for bioremediation of organic and inorganic contaminants. Also, Osman et al. (2022) explained the utilization of biochar for enhancing micro-environment by supporting microbial growth, reduction in contaminants dispersion, and accelerated rate of humification of composts, for effective degradation of pollutants. Xiao et al. (2023), discussed adsorption principles while reviewing lignocellulosic material uses for water treatment. Additionally, Warren-Vega et al. (2023) explored biochar as a potential solution for per/polyfluoroalkyl (PFAS) substances contamination in agricultural systems by analyzing the physicochemical properties of biochar, and its advantages and challenges. Moreover, Saeed et al. (2024) reviewed the use of PGPR-biochar-based remediating systems to manage hazardous PAHs in soil, focusing on the combined PGPR mechanism and biochar's impact on organic pollutant degradation. On the other hand, there are reviews available that explain the prospects of rhizoremediation for degradation of organic pollutants (Gerhardt et al. 2009), without exploring the prospects of biochar application. Furthermore, Kotoky et al. (2018) reviewed the rhizoremediation technique for removing PAHs from plants through synergistic interactions with their microbiome. They also provided reports on modern omics methodologies, like metagenomics, metatranscriptomics, metabolomics, and metaproteomics, to understand these plant–microbe activity patterns for efficient organic pollutant degradation. Therefore, the need of a review for application of biochar in rhizoremediation process has been realized. Given all the advantages of biochar in contaminant degradation and plant-growth promotion, this review elaborates an integrated approach which involves rhizoremediation of organic contaminants such as crude oil, PAHs, pesticides and antibiotics, along with the application of biochar to accelerate rhizoremediation process,

Table 1 Organic contaminants, their maximum permissible quantities in soil and human body, their health impact and sources of contamination

Contaminants	Maximum permissible value	Health impact	Source	References
PAHs	No pollution: < 0.200 mg kg^{-1}, low pollution 0.200–0.600 mg kg^{-1}, medium pollution 0.600–1.000 mg kg^{-1} severe pollution: > 1.000 mg kg^{-1}	Alterations in function of bone marrow, suppress humoral and cell-mediated immunity, induced infertility in male, tumour formation in organs, skin cancer, neurotoxicity	Industrial, mobile, domestic, and agricultural emissions, untreated sewage sludge, mining	Raja et al., (2022; Ailijiang et al., (2022)
TPHs	Normal: > 100 mg/ kg^{-1}; sensitive: 200 mg/ kg^{-1}; alert values: 1000 mg/kg^{-1}; intervention values: 500 mg/kg^{-1}; severe: 2000 mg/kg^{-1}	Heart damage, restricted plant growth, effects immune system, impact marine life and even death	Land-based runoff, spillage, leakage, drilling, transportation	Abdel-Shafy and Mansour, (2016)
Perfluoroalkyl and Polyfluoroalkyl Substances (PFAS)	8 ng kg^{-1} bw/week	Kidney cancer, liver cancer, pancreatic cancer, developmental issues and disrupt the thyroid system	Package food, sea foods, vegetables, Nonstick cookware, Personal care products	Schrenk et al., (2020)
Pesticides	0.1 mg kg^{-1} soil	Targets on the sex hormone disruption and reproductive performance affecting the endocrine activity, cause neurological and gastrointestinal symptoms which is fatal to the central nervous systems. Lathrogen compounds present in legumes pulses affects the brain neurotransmitter	Agriculture now accounts for 70 to 80% of total pesticide use. Other household activities, runoff and industrial manufacturing	Abdalla et al., (2023)
Antibiotics	20–32,000 ng l^{-1}	Co-resistance and cross-resistance complicate the dose–response relationship for ARGs. Leads to proliferation of harmful bacteria and opportunistic pathogens, and further lead to various diseases such as pseudomembranous colitis, intestinal disorders and colorectal cancer, affect adiposity and bone growth	Manufacturing process and undigested excretion by cattle and humans. Overuse and disposal lead to contamination of the environment	Jalal et al., (2015)
Polychlorinated biphenyls (PCBs)	Normal: > 1 mg/kg^{-1}: Moderate: 1 mg/kg^{-1} or more Severe: 10 mg/kg^{-1} or more	Irritation of lungs, gastrointestinal discomfort, changes in the blood and liver, and depression and fatigue, neurobehavioral and developmental deficits in newborns, diabetes, and and cause non-Hodgkin's lymphoma	Illegal or improper dumping of industrial wastes and consumer products; from leaks in old electrical transformers; or during the burning of some wastes in incinerators	Zani et al., (2013)

and plant growth, during the ecorestoration of contaminated soil.

Furthermore, the global biochar market is experiencing significant growth, driven by increasing demand for sustainable agricultural practices, waste management solutions, and environmental remediation technologies. Biochar market size is estimated at USD 2.05 billion in 2023, and is projected to grow 3.99 billion by 2032 at a compound annual growth rate (CAGR) of 13.9% from 2024 to 2032 (Mandaokar et al., 2021). The biochar market is anticipated to undergo substantial expansion, with its beginning worth of US $444.2 thousand predicted to escalate to a valuation of US $14,751.8 thousand by 2025 (Persistence Market Research 2024).

In 2023, North America dominated the market accounting for over 80.0% of large-scale and medium-sized manufacturers and holding a market share of 58.5% (Global Biochar Market Report 2024). In 2023, the agriculture sector was identified as the dominant application segment for biochar, contributing over 77.0% of the total revenue, highlighting its pivotal role in driving the biochar market (Global Biochar Market Report 2024). The global biochar market classifies the type of materials used for biochar production into various categories, such as agricultural waste, manure from animals, wood-based biomass, and various other sources (Amalina et al. 2022). The category of woody biomass dominates the market, representing approximately 50% of the overall demand (Popp et al. 2021), highlighting the utilization of lignocellulosic biomass for biochar production, driven by its favorable properties and widespread availability. Figure 1 illustrates the global distribution of some organic pollutants and global biochar market size.

This review provides a comprehensive mechanism of the impact of environmental applications of biochar-combined rhizoremediation for soils contaminated with organic contaminants, as well as the interactions between plants and biochar throughout the remediation process. This study investigates the potential of biochar as a catalyst to enhance the rhizoremediation of polluted soil and promote the growth of microbial communities. Additionally, this review highlights several bioengineered techniques used during biochar production to enhance the functionality of these compounds and supporting sustainable environmental management. It also outlines potential omics approaches to assessing the impact of biochar applications on microbial community dynamics and its role in the elimination of organic pollutants, providing a field for future research on using biochar in soil remediation. The findings of this comprehensive analysis and the insights derived from this review have the potential to greatly influence the progress made in tackling global environmental issues, while also paving the way for a more sustainable rhizoremediation approach to

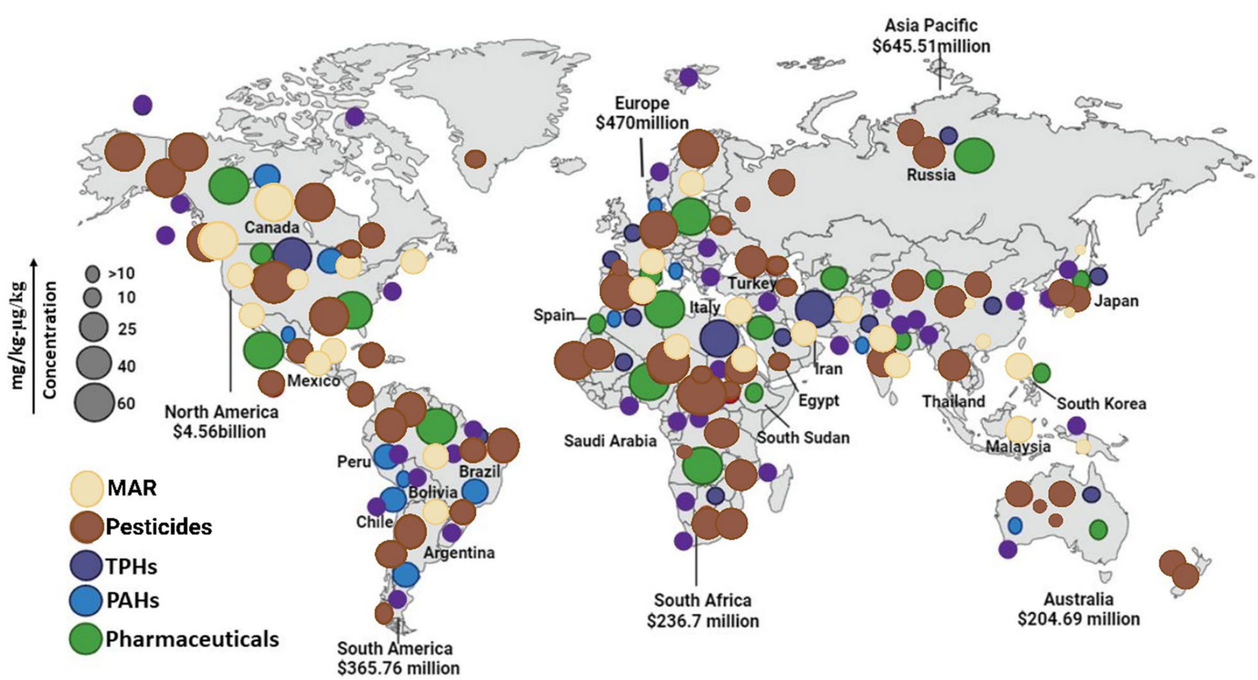


Fig. 1 Map showing the global biochar market size alongside the distribution of environmental contamination caused by pesticides, microbial antibiotic resistome (MAR), TPHs, PAHs, and pharmaceuticals in soil (Delgado-Baquerizo et al. 2022; Pesticide Atlas, 2022; Wilkinson, et al. 2022; Singha and Pandey 2021)

managing organic contaminants. Figure 2 illustrates different applications of engineered biochar and its role in the circular economy.

2 Different remediation techniques for organic pollutants

Organic pollutants negatively impact soil by affecting microbial populations, disturbing enzyme activity, distorting the composition and structure of organic matter (Sun et al. 2023a, b). These chemicals adhere to soil constituents and are often difficult to remove or degrade, resulting in the contamination of both surface and groundwater systems (Al-Hashimi et al. 2021). The physical remediation approach employs physical and mechanical barriers to separate, and remove contaminants from the soil, including capping, soil replacement, soil washing, and thermal desorption (Rajendran et al. 2022). Soil replacement involves removing contaminated soil and replacing it with uncontaminated soil, while soil washing is a method to isolate pollutants, and thermal desorption uses heat to remove volatile pollutants in soil (Ossai et al. 2020). Chemical remediation involves augmentation, leaching, and oxidation by using phosphoric acid, potassium phosphate, sulfuric acid, nitric acid, and hydrogen chloride (Wang et al. 2024a, b). In the process of chemical leaching, contaminated soil undergoes treatment involving water, chemicals, and various fluids that facilitate the extraction of contaminants through mechanisms such as ion exchange, precipitation, adsorption, and chelation (Wang et al. 2024a, b). Although these remedies can be effective, they often require substantial energy and infrastructure, along with high toxicity and costs, which limit their practicality (Azuazu et al. 2023; Yao et al. 2012a, b).

The biological method encompasses remediation techniques that utilize living organisms, including plants and microorganisms, to degrade contaminants present in the soil (Enyiukwu et al. 2021). Bioaugmentation, biostimulation, vermiremediation, and phytoremediation are biological techniques used to enhance the degradation of contaminants (Adewoyin et al. 2023). Bioaugmentation involves incorporating supplementary microbes to boost the native population, such as bacteria, fungi, and earthworms (Ameen and Al-Homaidan 2024). Biostimulation, on the other hand, modifies the environment to encourage native microbial activity by the incorporation of oxygen, nitrogen, carbon, and phosphorus to boost bioremediation process (Bhuyan et al. 2023).

Furthermore, rhizoremediation can effectively reduce the majority of pollutants without disrupting natural soil activities and reduces the costs by 60–80% compared to conventional physicochemical remediation techniques

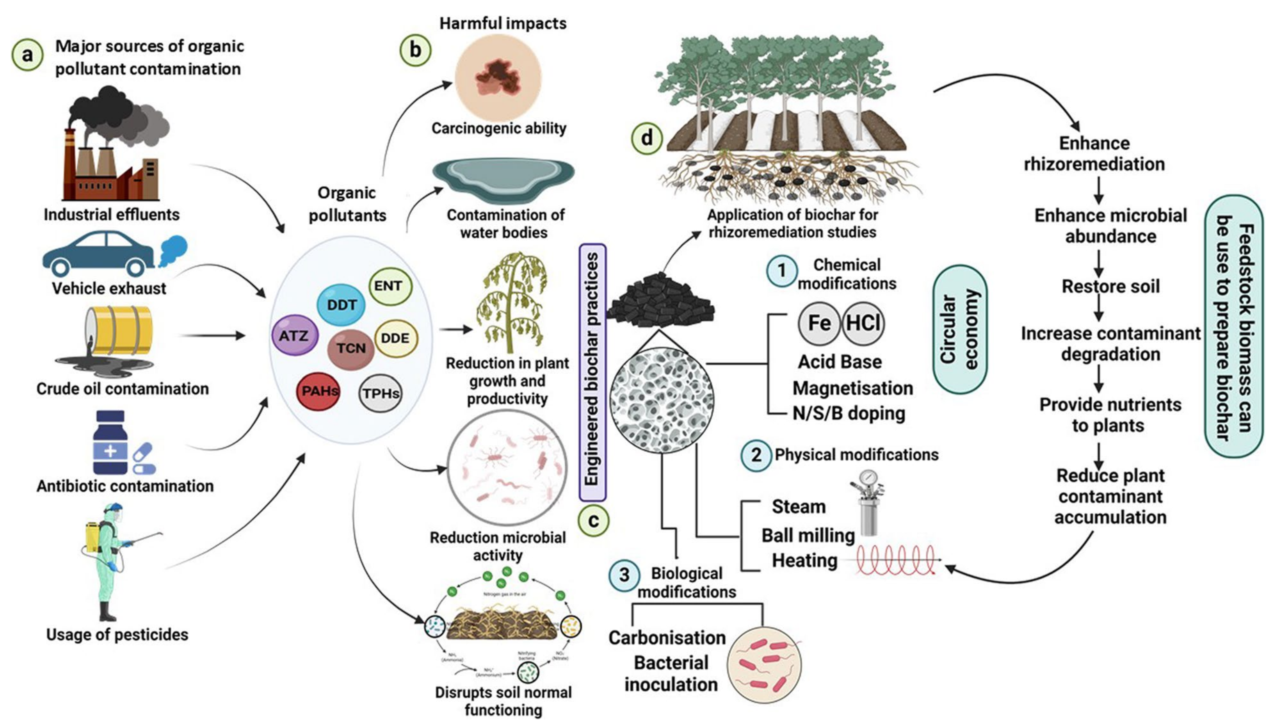


Fig. 2 **a** Major sources of organic pollution, **b** harmful impact of xenobiotics in ecosystem, **c** engineering of biochar through chemical, physical and biological methods, **d** application of engineered biochar in remediation processes, and the feedstock used in the remediation can further be used in biochar production to contribute to circular economy

(Mwegoha et al., 2016). Moreover, rhizoremediation has other advantages, including carbon sequestration, soil erosion management, fuelwood production, biodiversity preservation, and enhancement of landscape aesthetics, alongside contamination removal (Hu et al. 2012; Pandey et al. 2015). Additionally, indigenous microbes facilitate the degradation of contaminants in the rhizosphere, thereby reducing the risk of contaminant accumulation in plant tissues (Kotoky and Pandey, 2018). Furthermore, the plant growth-promoting attributes of these microbes enhance plant growth in contaminated soils while mitigating the oxidative stress caused by pollutants (Singha et al. 2018). Comparison of different remediation techniques and their cost effectiveness is listed in Table 2. A detailed mechanism of rhizoremediation for several organic contaminants is presented in the section below.

3 Rhizoremediation as a nature based eco-restoration process

Rhizoremediation involves the application of specific synergistic action of plants and microbes to metabolize and degrade contaminants in soil (Baboshin and Golovleva 2012). Plants employ various mechanisms such as phytoextraction, phytostabilization, phytovolatilization, rhizodegradation, rhizoextraction, and rhizofiltration to remove and degrade different organic pollutants (Das et al. 2024a, b; Das and Dash 2014). Moreover, the bacterial community near the rhizosphere can catabolize various contaminants directly due to their diverse physiological attributes (Kotoky et al. 2018). Plants such as *Lioum multiflorum* (Ryegrass) can degrade TPH pollutants by up to 90% when augmented with efficient organic pollutant -degrading microorganisms (Das et al. 2024a, b). Plant growth promoting rhizobacteria including *Acidobacter, Mycobacterium, Alteromonas, Pandoraea, Burkholderia, Dietzia, Arthrobacter, Staphylococcus, Streptobacillus*, *Kocuria, Marinobacter, Pseudomonas, Streptococcus*, and *Rhodococcus* play a crucial role in pollutant degradation along with supporting plant health by producing phyto-hormones, and protecting plants from pathogens (Das et al. 2024a, b; Shah et al. 2024).

3.1 Root exudates as a key ecological driver of rhizosphere microbial community modulation

Root exudates are chemical substances secreted by plants to interact with microorganisms in the rhizosphere (More et al. 2020). More than 20% of the carbon sequestered by plants through photosynthesis is released into the rhizosphere along with other compounds such as amino acids, phenolic compounds, organic acids, vitamins, secondary metabolites, polysaccharides, proteins and mucilaginous substances in the form root exudates (Heuermann et al. 2023). These highly complex substances can serve as nutrient sources for microbes establishing beneficial association, modulate soil structure and reduce competition from neighboring plants.

Corgié et al. (2003) reported that *Lolium perenne* L. cultivated in soil contaminated with petroleum hydrocarbons showed 86% phenanthrene biodegradation within 3 mm from the roots, 48% in the 3–6 mm interval, and 36% in the 6–9 mm range. The parallel bacterial gradient indicated the elevated abundances of PAH-degrading bacteria near the roots, with the highest rates of organic pollutant degradation and the dominant microbial degraders primarily located within 3 mm of the root surface. Upon the introduction of root exudates from ryegrass, there was a notable shift in the population for phenanthrene degraders, predominantly towards the *Actinobacterium, Arthrobacter* spp., *Pseudomonas stutzeri* and *Pseudoxanthomonas mexicana* (Rohrbacher and St-Arnaud 2016). Similarly, *Medicago sativa* root exudates promoted microbial-mediated petroleum hydrocarbon biotransformation, exceeding 90% in the rhizosphere compared to less than 50% in bulk soil and unplanted control soils (Eze and Amuji 2024).

Compounds like terpenoids and flavonoids released by plant-roots are structurally similar to aromatic hydrocarbons (Das et al. 2024a, b; Bisht et al. 2015). Consequently, structural analogy enhances the degradation of organic pollutants by promoting co-metabolic processes, involving the oxidation and mineralization of petroleum hydrocarbon molecules (Eze and Amuji 2024). Also, plants secrete malic and citric acids acting as co-metabolites to enhance the bioavailability of organic contaminants (Wu et al. 2017a, b). Buckner (2018) reported a significant reduction in TPH levels from 4330 mg kg^{-1} to less than 120 mg kg^{-1} over a 22-week period in soil planted with ryegrass.

A recent study by Hu et al. (2018) demonstrated that benzoxazinoids (BXs) altered the composition of root-associated fungal and bacterial communities while enhancing jasmonate signalling to strengthen plant defence mechanisms. Similarly, root exudates attract beneficial microorganisms that enhance nitrogen uptake by enriching diazotrophs for nitrogen fixation, improving nitrogen bioavailability, and conserving soil nitrogen. *Phomopsis liquidambaris* boosts phenolic and flavonoid synthesis in *Arachis hypogaea* (peanuts), and stimulated nodulation gene expression in *Bradyrhizobium*, causing increased crop yields (Xie et al. 2022).

Volatile organic compounds (VOCs), such as acetoin and 2,3-butanediol, facilitate communication among plant-associated microbes, triggering induced systemic resistance (ISR) as bioprotectants (Ryu et al. 2004). Moreover, plants possess the capability to improve degradation processes via the root exudation of various enzymes,

Table 2 Comparison of different remediation techniques based on operation cost and environmental compatibility

Type of Remediation	Contaminant types	Remediation techniques	Contaminants Removal rate (%)	Environmental risk	Approximate Cost ($/m3)	Compounds produced	Reference
Chemical method	Primarily organic pollutants (e.g., hydrocarbons, solvents)	Chemical Oxidation	60–80	Risk of toxic intermediates, soil toxicity	$100–500	Chlorinated phenols, Aldehydes, quinones, hydroxylated PAHs,	Atemoagbo, (2024)
		Solvent Extraction	60–80	Risk of toxic intermediates, soil toxicity	$150–600		
Physical method	Mainly inorganic (metals, salts), some organics	Soil Vapor Extraction	40–70	Generates secondary waste, soil disturbance	$10,000–25,000	Chelating agents (e.g., EDTA), carbon monoxide (CO), nitrogen oxides (NOx), and dioxins	Lutes et al., (2022)
		Groundwater Pumping	40–70	Generates secondary waste, soil disturbance	$50–250		
		Incineration	80–95	Generates secondary waste, soil disturbance	$200–1500		
Biological	Mostly organic pollutants, some inorganic	Bioremediation	80–95	Eco-friendly, improves soil health	$50–100	Carbon dioxide (CO_2), Methane (CH_4), Nitrous oxide (N_2O), Phenolic Compounds	Atemoagbo, (2024)
	Both organic (PAHs, pesticides) and inorganic (metals, arsenic)	Phytoremediation	80–90	Eco-friendly, improves soil health	$60–120	Plants can partially degrade organic contaminants such as PAHs, PCBs, and pesticides, producing toxic intermediates (e.g., phenols, quinones, and aldehydes) that may accumulate in plant tissues and contaminants can biomagnifies through the food chain	Atemoagbo, (2024); Gerhardt et al., (2009)
	Both organic (PAHs, pesticides) and inorganic (metals, arsenic)	Rhizoremediation	90–99	Eco-friendly, enhances ecosystem recovery	$10–50	Complete utilization of organic pollutants with the help of mutual plant and microbe interactions. May produce quinones and catechols which can further metabolise by microbial community. Production of CO_2 during microbial metabolism is taken up by the plants	Gerhardt et al., (2009)

such as laccases, phenol oxidases, and peroxidases. These enzymes promote the oxidation of different organic pollutants, resulting in their decomposition into intermediate products. The enzymatic breakdown derived from microbial activity is acknowledged as the primary mechanism responsible for the degradation of different organic pollutants (Das et al. 2024a, b).

3.2 Microbial mechanisms in the rhizosphere for contaminant removal

Bacterial sp. such as *Pseudoxanthomonas, Burkholderia, Mycobacterium, Prevotella, Cellulomonas, Actinobacillus, Anaeromyxobacter, Paraburkholderia, Sphingomonas, Novosphingobium, Acetivibrio, Acetobacter, Cycloclasticus, Microbulbifer, Gordonia*, and *Micrococcus*, are the most abundant rhizospheric community involved in organic compound degradation (Das et al. 2024a, b; Das et al. 2023; Kumari and Das 2023; Kotoky and Pandey 2020; Singha et al. 2018). However, the majority of bacterial species lack the requisite enzymes for the degradation of all organic pollutants; thus, it is typically achieved through the application of a bacterial consortium possessing diverse enzyme systems (Kebede et al., 2021). A study by Sampaio et al. (2019) demonstrated that two bacterial strains, *Bacillus* sp. and *Pseudomonas aeruginosa*, successfully colonized *Rhizophora mangle* roots, enhancing plant protection, propagule germination, and degraded over 80% of PAHs in sediment. Similarly, *Zea mays* plants amended with bacterial consortium (*Bacillus thuringiensis* SG4 and *Bacillus* sp. SG2), resulted in 85% degradation of Cypermethrin (insecticide) in rhizosphere (Bhatt et al. 2022). Additionally, during a 3-day treatment period, bacteria such as *Sporohalobacter orenetal, Oscillospira* sp., and *Clostridium prazmowski* were able to break down paraquat by 86.22%, 79.35%, and 80.26%, respectively (Han et al. 2014).

Plant growth-promoting microorganisms (PGPMOs) significantly impact on the rhizosphere environment, enhancing the production of growth-promoting hormones, enzymes, siderophores, and biosurfactants. For example, consortium comprising *Acidocella aminolytica* and *Acidobacterium capsulatum*, applied through *Medicago sativa* L., degraded up to 91% of diesel fuel in soil and increased plant growth by 66% within 60 days (Eze et al. 2022). Organic acids produced by microorganisms decreased soil pH and increased PAH solubility (Yesankar et al. 2023). These beneficial rhizobacteria protect the plants against diseases, provide essential nutrients, and promote plant development (Oleńska et al. 2020). Biosurfactants, amphiphilic substances, are synthesized by microorganisms to create micelles in the presence of PAHs, enhancing their bioavailability and biodegradation. Additionally, the formation of biofilms by the bacteria allows them to aggregate within a self-generated adhesive material, enhancing their ability to thrive and adhere to contaminated surfaces (Das et al. 2023). Liu et al. (2015) observed an increase in the biomass of *Festuca arundinacea* L. and the degradation of PAHs during phytoremediation treatments utilizing bacteria with plant growth-promoting traits and the ability to produce biosurfactants in oil-contaminated soil.

The main catabolic pathways in bacteria for breakdown of the aromatic compounds start with the ortho and meta-cleavage of catechol molecules (Yong et al. 2015). Aerobic degradation involves the activation of hydrocarbon molecules by the incorporation of one or two oxygen atoms (Boll and Heider, 2020). This process is facilitated by substrate-specific terminal oxygenases or subterminal oxidation. Four categories of enzymes are implicated in aromatic hydrocarbons: Rieske non-heme iron oxygenases (RNHO), flavoprotein monooxygenases (FPM), soluble di-iron multicomponent monooxygenases (SDM), and CoA ligases (Kumari and Das 2023). The activation enhances the hydrocarbon solubility in water, designates a reactive site, and adds an additional reactive site for future reactions (Sun et al. 2022). In aliphatic hydrocarbons, the activated molecule is transformed into an alkanol, then oxidized to an aldehyde, and ultimately turned into a fatty acid. A fatty acid is conjugated to CoA, resulting in the formation of acyl-CoA, which is then processed by β-oxidation to produce acetyl-CoA. The ultimate result is acetyl-CoA, which undergoes catabolism in the Krebs cycle and is completely oxidized to CO_2 (Das et al. 2023).

Enzymes, including alkane 1-monooxygenase, alcohol dehydrogenase, cyclohexanol dehydrogenase, and cyclohexanone 1,2 monooxygenase, facilitate the bacterial breakdown of organic chemicals found in crude oil-contaminated soils (Das et al. 2023). The non-heme integral membrane alkane monooxygenase, which is encoded by *alkB*, plays a crucial role in the initial activation of aerobic aliphatic hydrocarbon metabolism (Garrido-Sanz et al. 2019). The genes *todC, bedC*, and *bph* are responsible for encoding the subunits of benzene-, toluene-, and biphenyl- 2,3-dioxygenase, respectively (Liu et al. 2024). The ring-hydroxylating dioxygenase α-subunit (*RHDα*), which is encoded by the *nah* gene, plays a crucial role in the hydroxylation of PAHs. This process is followed by decarboxylation, which is facilitated by enzymes encoded by the *dmp/xyl* genes (Song et al. 2021).

Additionally, the *Pseudomonas* sp. strain ADP utilizes atrazine as its sole carbon source, with three key enzymes driving the initial stages of atrazine degradation. The first enzyme, *AtzA*, mediated the hydrolytic dechlorination of atrazine, producing non-toxic hydroxyatrazine, which plays a vital role in its biological breakdown. Subsequently, *AtzB* facilitates the deamination of hydroxyatrazine, forming N-isopropyl cyanuric amide. Finally, *AtzC* converts N-isopropyl cyanuric amide into cyanuric acid and isopropylamine. Through this pathway, atrazine is ultimately broken down into CO_2 and ammonia (Roychoudhury et al. 2024). Similarly, antibiotics can be directly degraded by the method of antibiotic inactivation, specifically via hydrolysis, group transfer, and redox processes. Hydrolysis is therapeutically significant, especially for *β*-lactam antibiotics; however, group transfer methods are more varied and include modifications such as acyltransfer, phosphorylation, glycosylation, nucleotidylation, ribosylation, and thiol transfer (Vera-Baquero et al. 2024).

The effectiveness of rhizoremediation is significantly dependent both on the optimal selection of plant species and genotypic varieties, which play crucial role for developing effective remediation strategies (Chaturvedi et al. 2023). Several biotic and abiotic parameters, including type of soil, pollutants concentration, pH and temperature of the soil, available organic matter and nutrients content, soil moisture, porosity, water holding capacity, available soil oxygen, solubility of contaminants, abundance of indigenous microflora, and their metabolic ability, act as determining factors for variations in organic compound degradation (Das et al. 2024a, b). Additionally, the release of carbon and nitrogenous substances in the form of root exudates also plays major role in shaping the microbial diversity in rhizosphere (Bhuyan et al. 2022). Thus, the application of biochar is emerging as a promising strategy to address soil limitations associated with the rhizoremediation process during organic degradation (Kumar et al. 2024). Its high porosity, superior adsorption capacity, and potential for climate change mitigation make biochar an effective catalyst for accelerating rhizoremediation processes (Ghadirnezhad Shiade et al. 2024). Section 4 provides a concise overview of biochar applications aimed at enhancing its efficiency for contaminant removal.

4 Biochar as a catalyst for rhizoremediation of organic contaminants

Biochar, a byproduct of pyrolysis, is widely used to improve soil quality and treat soils contaminated with organic and inorganic substances (Rizwan et al. 2023). Biochar is rich in nutrients like potassium, magnesium, calcium, and phosphorus, and can also produce dissolved organic material, potentially providing plants and microbes with accessible nutrients (Ndoung et al. 2021a, b). Wang et al. (2017a, b), showed that biochar application significantly increased the microbial population upto 7.5 $\log^{10}$ CFU g^{-1}. The application of biochar has been shown to enhance the cation exchange capacity of soil (15.5–16.1 cmol kg^{-1}), increasing proliferation of nitrogen-fixing bacteria (Lawson et al. 2019; Bolan et al. 2024a, b). A 6-month study found a significant increase in nitrogen cycling gene (*nirS*) in soil amended with biochar (10%) derived from Switchgrass pyrolyzed at 350 °C (Ducey et al. 2013). Biochar has been found to have positive effects on crop yield and productivity, with a reported increase of 10% in crop yield (Zhang et al. 2021a, b, c, d; Ren et al. 2020). Moreover, in contaminated environments with low carbon content and acidic pH, the application of biochar, characterized by its labile carbon content and alkaline pH, can significantly enhance the relative abundance of microorganisms (Zhang et al. 2019). The micro- and meso-porous structures of biochar create an appropriate and secure habitat for microorganisms. The surfaces of biochar are characterized by a variety of functional groups, such as carbonyls (COO^-), carbonates ($CaCO_3$), phosphates (PO_4^{3-}), and additional alkaline compounds. These components contribute to an increase in soil pH, thereby fostering a more conducive environment that improves nutrient bioavailability for both plants and microorganisms (Geng et al. 2022). Biochar has considerable potential to enhance rhizoremediation of environmental contaminants. However, its effectiveness depends on various characteristics, such as the raw materials used and the pyrolysis temperatures, which can influence soil microbial responses and pollutant removal efficiency in the rhizosphere (Narayanan and Ma 2022; Murtaza et al. 2023). The application of biochar in rhizoremediation for various organic contaminants has been discussed below.

4.1 Application of biochar in rhizoremediation of PAH

The adsorption of PAHs onto the porous structure of biochar occurs due to π-π interactions between the benzene rings of the PAH compounds and the aromatic structures present in the biochar (Anyika et al., 2015) The degradation of PAHs in soil greatly affected its bioavailability, the activity of soil microorganisms, and the exudates released by plants (Singha et al. 2020; Kotoky et al. 2020; Das et al. 2024a, b). Further the application of biochar stimulates microbial activity and plant growth, thereby enhancing PAH bioremediation process (Kong et al. 2018).

It has been reported that even the application of 2% biochar significantly enhances rhizoremediation by *Lolium perenne*, demonstrating the highest efficacy in PAH removal (Li et al. 2020a, b, c, d, e, f). Beesley et al. (2011) demonstrated that the use of hardwood-derived biochar reduced the levels of accessible PAHs by more than 50%. In a study, maize and wheat straw biochars pyrolyzed at 300 °C and 500 °C were applied to PAH-contaminated soils, followed by a 90-day growth period of *Lolium multiflorum* L. The results suggested that 500 °C wheat straw biochar, with its greater surface area and nutrient content, significantly enhanced PAH rhizoremediation, reducing PAHs by 62.5% (Guo et al. 2024). Additionally, rhizoremediation of PAHs spiking polluted soil using 5% biochar and 5% compost and a consortium of *Actinobacter bouvetii, Stenotrophomonas rhizophila*, and *Pseudomonas poae*, and *Pseudomonas rhizosphaerae,* resulted in the removal of 85% PAHs in raygrass rhizosphere (Hussain et al. 2018). Moreover, the health risks associated with PAHs in vegetables were assessed by growing *Brassica chinensis* L. (Chinese cabbage) in both biochar-amended soil (derived from walnut shells and corn cobs) and control soil. The biochar amendments significantly reduced the dissipation of Σ16PAHs up to 73.59–77.01%, which primarily immobilized the PAHs within biochar micropores (Yang et al. 2022). Additionally, Li et al. (2020a, b, c, d, e, f), evaluated the combined use of biochar and ryegrass for the degradation of PAHs, including Ph (phenanthrene), Py (pyrene), and B[a]P (benzo[a]pyrene), in a root box. Subsequently after 100 days, the biochar-rhizosphere zone exhibited greater PAHs removal (49–51%) as compared to the rhizosphere alone (41–49%) and biochar alone (39–44%). Similarly, biochar derived from sewage sludge significantly enhanced lettuce biomass and lowered PAH concentrations in soil by 58–63%, as well as reduced the uptake of 16 PAHs by 56–67% (Zhang et al. 2021a, b, c, d). Biochar applications also decreased the PAH uptake in cucumbers by 44–57% (Brennan et al. 2014). In addition, biochar synthesized from pine needles lessened the PAH uptake in rice, due to a decrease in freely available PAHs in the soil after the application (Zhu et al. 2018).

4.2 Application of biochar in rhizoremediation of crude oil

Petroleum constitutes a multifaceted amalgamation predominantly consisting of saturated and aromatic hydrocarbons, resins polymers, and asphaltenes (Liu et al. 2014). The utilization of biochar in contaminated soils demonstrates advantages in the removal of petroleum hydrocarbons when compared to control conditions (Dike et al. 2021; Dike et al. 2022a, b; Wei et al. 2024). Aziz et al. (2020) and Wang et al. (2017a, b) reported that biochar treatment resulted in higher removal of total petroleum hydrocarbon (TPH), ranging from 47% to 76%, compared to the control treatment (28–36%).

Petroleum contaminants in soil adversely impact microbial activity and diversity, as well as reduce plant growth, development of root, stem, and grain production (Ullah et al. 2021). In a study the application of sugarcane bagasse (SB) biochar along with *Bacillus* sp. MN54, showed higher growth of maize (*Zea mays* L.) in diesel-contaminants soil. Co-supplementation increased physiological (25–48%) and agronomical (38–47%) traits and 77% of the petroleum hydrocarbons were removed in biochar treated plants as compared to the control (Ali et al. 2021). Additionally, the effects of biochar amendment with ryegrass resulted in enhanced removal of TPHs and increased microbial counts, with total n-alkane removal rate of 45.83% (Han et al. 2016). Hussain et al. (2022) reported that the combination of biochar and ryegrass for phytoremediation resulted in a 65% hydrocarbon removal rate, significantly higher than the control (47%). Similarly, Hashmi et al. (2024) and Tammeorg (2017) observed that biochar-assisted phytoremediation increased hydrocarbon removal by 32–45% as compared to phytoremediation without biochar. Furthermore, Hussain et al. (2022) and Saeed et al. (2021) noted that treatments incorporating both biochar and plants significantly enhanced hydrocarbon removal relative to phytoremediation alone. Yousaf et al. (2022) assessed biochar-assisted phytoremediation using white maize, clover, ryegrass, alfalfa, and wheat in combination with wood-chip biochar. The study found that hydrocarbon degradation was higher in the biochar-assisted treatments (34–68%) compared to treatments using only biochar (27%) or phytoremediation (9–60%) (Barati et al. 2017). The reduction in TPHs and the average microbial metabolic rate were elevated in soils amended with biochar, with increases of 21.76% and 37.73% for barley biochar and 20.36% and 45.18% for oat biochar (Barati et al. 2017). In another study, remediation of aged TPH-contaminated soil was conducted using Italian ryegrass with 5% compost and 5% biochar with an immobilized microorganism. The results demonstrated that the highest TPH removal (40%) was achieved with the combined application of these amendments (Curiel-Alegre et al. 2024). This enhanced TPH removal was associated with increased rhizospheric activity, as evidenced by substantial increases in root biomass (85–159%) and bacterial counts (Yuan et al. 2023). Rhizoremediation of petroleum-contaminated soil using *Vetiveria zizanioides* L. combined with *Acinetobacter venetianus* and biochar resulted in 50–70%TPH removal within 6 months (Lin et al. 2022).

4.3 Application of biochar in rhizoremediation of pesticides

Pesticides are harmful chemicals extensively used to manage, eliminate, repel, or control pests as well as unwanted plants and animals, or microorganisms in agriculture cultivation systems (Hashmi 2021). Biochar application enhances pesticide sorption in soil and increases its bioavailability for soil microorganisms (Khalid et al. 2020). Deng et al. (2014) demonstrated that increasing the concentration of biochar to 5% significantly reduces atrazine concentrations in soil. Yang et al. (2010)

observed that application of biochar derived from cotton straw led to decreased levels of chlorpyrifos and fipronil in soil and lowered pesticide accumulation in *Allium tuberosum* (Chinese chives). Additionally, biochar promoted the polymerization of organic molecules, and potentially increased soil organic carbon and productivity (Han et al. 2020; Awad et al. 2012). Maize plants cultivated in soil contaminated with 100 and 200 mg kg^{-1} of chlorpyrifos (CP) experienced substantial toxicity, with an 84% reduction in growth at 200 mg kg^{-1} CP. Nevertheless, the application of compost and biochar at 0.50% increased the fresh weight of maize by 2.8-fold and fourfold, respectively (Gray et al. 2023). The effectiveness of metribuzin (MB) remediation using a bacterial consortium (*Rhodococcus rhodochrous, Bacillus tequilensis, Bacillus aryabhattai* and *Bacillus safensis*) immobilized on biochar demonstrated 96% MB degradation, while only 29.3% degradation was observed in untreated soil (Wahla et al. 2019). Karthikeyan et al. (2021) provided comprehensive insights into the use of trees, shrubs, and grasses, for the degradation of pesticides in soils. Specific plants, such as certain *Cucurbitaceae* cultivars, exhibited higher uptake of DDE, attributed to their elevated exudation of LMW (low molecular weight) organic acids (Chandra et al. 2017). Similarly, results were obtained for lindane (Abhilash et al. 2013), and cypermethrin (Dubey and Fulekar 2013). Further, another study investigated the impact of Sudan grass root exudates on organochlorine pesticide (OCP) degradation and soil microbial characteristics and results exhibited that root exudates significantly enhanced OCP removal, achieving up to 79.32% degradation (Zhou and Pan 2023). Yu et al. (2009), reported that adding 1% biochar to soil led to a significant reduction in plant absorption rates of carbofuran and chlorpyrifos, measured at 25% and 10%, respectively, compared to soil without biochar.

4.4 Application of biochar in rhizoremediation of antibiotics

Antimicrobial resistance is a global health concern, exacerbated by horizontal gene transfer driven by mobile genetic elements (MGEs), which increases the transmission rate of antibiotic resistance genes among microbial communities (Pai et al. 2023). A study found that biochar pyrolyzed at temperatures above 500 °C was significantly more effective at absorbing antibiotics (ceftiofur and florfenicol) compared to biochar pyrolyzed at lower temperatures (Zaman et al. 2023). Additionally, research revealed that a single-stage system can achieve a 75% removal of tetracycline by utilizing 63.0 g of magnetic chicken-bone biochar over a period of 12 h. However, in a two-stage stirred adsorber, magnetic chicken-bone biochar could effectively eliminate 96% of the targeted tetracycline (100 mg L^{-1} solutions) within 180 min (Oladipo et al. 2018). A recent study combined waste-fungus-chaff-biochar (WFCB) with *Herbaspirillum huttiense* to degrade the antibiotics enrofloxacin (ENR) and oxytetracycline (OTC). The results showed that this combined material effectively removed OTC by 41.9% and ENR by 40.7% (Katiyar et al. 2022).

A recent study showed that the presence of 131 ARGs was significantly reduced by 0.5% (w/w) rice straw biochar in unplanted soil. However, the effectiveness of this reduction was less noticeable in soil containing *Brassica chinensis* L. plants (Hashem et al. 2020). Additionally, a study showed that the bacterium *Microbacterium* sp. WHC1 was able to remove 98% of ciprofloxacin (CIP) in the presence of root exudates from *Eichhornia crassipes* (Xue et al. 2022). The incorporation of biochar into the soil was found to significantly reduce the frequency of gene transfer (conjugation) between bacteria, thereby effectively inhibiting the replication of ARGs. This highlights the strong inhibitory effect of biochar on ARGs through its interaction with bacteria (Shah, 2024). Wang et al. (2024a, b) found that microbial degradation intensified closer to plant roots, as rhizomes enhanced the levels of dissolved organic carbon and dissolved oxygen, which in turn increased microbial abundance and improved sulfonamide degradation. *Brassica juncea* and *Lolium multiflorum* were able to remove 28.00–92.89% of tetracycline and 88.80–99.50% of sulfonamides, respectively (Cui et al. 2021). Guo et al. (2020) showed *Myriophyllum aquaticum* removed 88% and 99% of tetracycline at a concentration ranging from 100 to 10,000 μg L^{-1} over a short growth period of 7 days. Adesanya et al. (2020) investigated the sorption of sulfamethoxazole onto the roots of cattail and switchgrass in a laboratory-scale study. Additionally, *Arabidopsis thaliana* was observed to metabolize a significant portion of sulfamethoxazole, leaving just 1.1% of the original compound after 10 days (Huynh and Reinhold 2019).

Figure 3 depicts the applications of biochar in organic contaminant degradation and plant growth promotion along with microbial growth. Table 3 shows the application of different biochar amendments used in remediation of different organic contaminants and their remediation efficiencies.

5 Impact of biochar application on soil microbial community structure and their functional diversity

To analyze various enzyme activities and gain a comprehensive understanding of the genetic and metabolic factors related to the impact of biochar application in bioremediation studies, some omics approaches are described below.

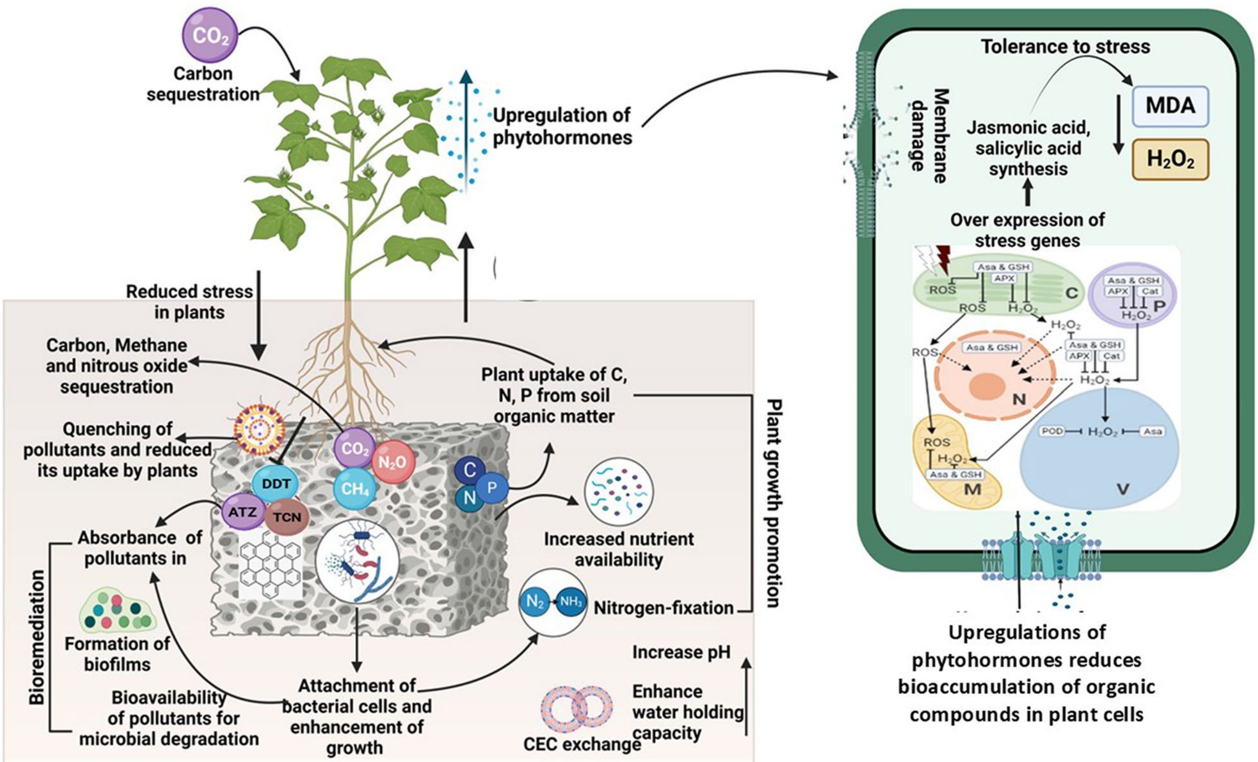


Fig. 3 Applications of biochar in enhancing the degradation of organic contaminants, improving bioavailability, promoting plant growth and stress management, supporting microbial proliferation and biofilm formation, enhancing nutrient availability, capturing carbon, and contributing to geochemical cycling

5.1 Metagenomics analyses

Metagenomics is an innovative approach to studying microorganisms in specific environments by analyzing their functional genes (Kouselya et al. 2022). Cui et al. (2024) conducted metagenomic analyses of field-aged biochar within the soybean rhizosphere. The findings demonstrated an elevated abundance of *Bradyrhizobium*, suggesting that aged biochar improves nitrogen availability and modifies nitrogen-cycle microbial communities, presenting a feasible strategy for enhancing nitrogen supply in continuous soybean cropping systems.

However, Zhao et al. (2022a, b) explored the effects of rape straw biochar (1, 2, and 4% w/w) on the rhizoremediation of PAH-contaminated soil using ryegrass. Application of biochar altered the rhizosphere bacterial community, increasing α-diversity and the abundance of *Pseudomonas* and *Zeaxanthinibacter*. The bacterial community showed strong correlation with PAH degradation. Further, a 150-day pot experiment was conducted utilizing rice husk biochar to facilitate the remediation of soils that are co-contaminated with PAHs and heavy metals employing alfalfa (Li et al. 2024a, b, c, d, e, f). The application of biochar resulted in a progressive increase in the population of PAH-degrading microorganisms, demonstrating a positive correlation with the reduction of PAHs. The intervention led to a decrease in bacterial richness and diversity; however, it promoted the proliferation of significant genera including *Steroidobacter, Bacillus*, *Mycobacterium* and *Sphingomonas*, which played a role in the degradation of PAHs and the immobilization of heavy metals.

Hydrocarbon pollutant soil sites can further act as reservoirs for antibiotic resistance genes (ARGs) (Das et al. 2021a, b). Field trials with *Brassica juncea* and *Lolium multiflorum* demonstrated that biochar application significantly altered the distribution ARGs and effectively restricted their transmission from the rhizosphere to the root, leading to a 1.2–2.2% reduction in ARG abundance. Microbial community composition played a crucial role in this process, with bacterial communities accounting for 43% of the observed ARG variation. Furthermore, metagenomic analysis of antibiotic-contaminated agricultural soil indicated that certain bacterial taxa, including *Steroidobacter* (Proteobacteria), *Iamia*, *Parviterribacter*, and *Gaiella (Actinobacteria*), exhibited strong positive correlations with sulfonamide degradation, contributing to an 8–26% reduction in antibiotic residues following biochar application (Zhang et al. 2021a, b, c, d). In

Table 3 Biochar amendments used in remediation of different organic contaminants

Pesticides			
Contaminants	**Biochar Feedstock**	**Remediation (%)**	**Reference**
Carbofuran and chlorpyrifos	Wood chip residues	51.00 and 44.00	Yu et al., (2009)
Deisopropyl atrazine	Poultry litter	23.31	Uchimiya et al., (2010)
Simazine and atrazine	Green waste	58.75 and 34.25	Zheng et al., (2010)
Pentachlorophenol	Rice straw	96.25	Lou et al., (2011)
Dibromochloropropane	Almond shell	100	Klasson et al., (2013)
Simazine	Hardwood residues	85.65	Jones et al., (2011)
Pentachlorophenol	Bamboo residues	42.00	Xu et al., (2012)
Bentazone and aminocyclopyrachlor	Hardwood chip	50.00	Cabrera et al., (2014)
Sulfamethazine	Plant bur cucumber	86.00	Rajapaksha et al., (2014)
MCPA	Wooden box residues	150.00	Muter et al., (2014)
Antibiotics residues			
Sulfamethazine	Wood chip residue	27	Teixidó et al., (2011)
Tetracycline	Rice straw	71.18	Liu et al., (2012)
Sulphamethoxazole	Bamboo biomass	76	Yao et al., (2012a, b)
Methyl-pyrimidine	Sugarcane bagasse	97	Qin et al., (2019)
Naproxen	Agriculture residues	95	Mojiri et al., (2019)
Diclofenac	Agriculture residues	96	Mojiri et al., (2019)
Ibuprofen	Agriculture residues	98	Mojiri et al., (2019)
Thiazole	Sugarcane bagasse	61.94	Qin et al., (2019)
Tetracycline	Rape stalk residues	37.97	Tan et al., (2019)
Levofloxacin	Maize residues	67.55	Chen et al., (2019)
Norfloxacin,	Pine residues	50.34	Pan, (2020)
Aromatic hydrocarbons			
Phenanthrene, 2–4-dichlorophenol	Wood Chip residue	43.70% and 84.7%	Gu et al., (2016)
PAHs	Wheat straw	74.81%	Cao et al., (2016)
PAHs	Coconut waste residues and orange waste residues	34.88–72.32%	De Jesus et al., (2017)
PAHs	Sawdust and wheat straw	3-ring PAHs by 69.95% and 4-, 5-, and 6-ring PAHs by 45.96%, 37.92%, and 30.66%	Kong et al., (2018)
PAHs	Maize straw and bamboo residues	84.31%	Rombolà et al., (2019)
Di-chlorophenyl-dichloroethylene (DDE), pyrene and polychlorinated biphenyl	Wood Chip residue	37% and 41%	Li et al., (2019)
PAHs	Maize straw	82.71%	Li et al., (2019)
PAHs	Sludge derived residue	87%	Hung et al., (2020)
Crude oil	Walnut shell and pine wood chip	75	Mukome et al., (2020)
PAHs	Wood chip residues	97	Ukalska-Jaruga et al., (2020)

another investigation, the addition of 5% biochar derived from maize showed the enhancement of *Proteobacteria* abundance 73.54% ± 3.11 and 67.26% ± 1.48%, respectively, in the rhizosphere of *Thalassia hemprichii (*Zhang et al. 2021a, b, c, d). Additionally, biochar derived from rice straw (500 °C) in a biostimulation treatment resulted in a substantial increase in the presence of various bacterial phylum/classes, including *Gammaproteobacteria, Actinobacteria, Sphingomonadales,* and *Alphaproteobacteria,* in crude oil contaminated soil, with a degradation rate of 71.0% (Tang et al. 2021). The presence of biochar can lead to higher populations of certain bacteria, like *Clostridium, Bacillus, Sporomusa, Desulfosporosinus,* and A*licyclobacillus*, which belong to the *Firmicutes* and *Bacteroidetes* in plants rhizosphere (Sarma et al. 2024).

5.2 Transcriptomics analyses

Transcriptomics involves the use of all RNA sequences corresponding to DNA from gene coding regions. This is achieved through various technologies like RNA-seq, microarray, or real-time PCR (Hrdlickova et al. 2017). Plants exposed to the herbicide atrazine (ATZ) undergo significant transcriptomic changes to detoxify and degrade the compound. RNA sequence analysis of *Medicago sativa* growing in aztrazine contaminated soil, revealed upregulated genes linked to oxidation–reduction, conjugation, hydrolysis, and cysteine biosynthesis (Zhang et al. 2016). Additionally, Hewitt et al. (2023) demonstrated that biochar-amended soils enhance microbial and plant root gene expression, promoting soil and plant health. Beneficial microbial genes, including those involved in nitrogen fixation (*nifH*), nutrient cycling (*amoA, narG*), and biodegradation (*PAH-RHDα*), were upregulated. Gene ontology analysis revealed enrichment in nitrogen metabolism, organic compound metabolism (PAH), biosynthesis of peptides, and other organic macromolecules, and oxidoreductase activity, suggesting the potential application of biochar to improve rhizoremediation and soil health sustainably. Thereafter, Yang et al., (2024) showed that the transcriptome analysis of tobacco leaves at 60 and 100 days in a pesticide-contaminated environment identified 6561 differentially expressed genes (DEGs) in response to different biochar application rates (0, 600, and 1800 kg ha^{-1}). KEGG pathway analysis revealed that essential pathways, such as carbon fixation (ko00710), photosynthesis (ko00195), and starch and sucrose metabolism (ko00500), exhibited significant upregulation at the optimal biochar dosage (600 kg ha^{-1}) while showing downregulation at the elevated dosage (1800 kg ha^{-1}).

A biochar-intensified phytoremediation experiment assessed maize and wheat straw biochars (pyrolyzed at 300 °C and 500 °C) for PAH removal from ryegrass (*Lolium multiflorum* L.)-polluted soil. KEGG analysis showed upregulation of key PAH degradation pathways, including benzoate (ko00362) and PAH degradation (ko00624), highlighting biochar's role in enhancing rhizosphere-mediated bioremediation (Guo et al. 2024). Additionally, Wu et al. (2024) utilized high-throughput qPCR and sequencing to study the rhizosphere of pakchoi (*Brassica chinensis*) treated with biochar derived from composted pig manure. Their analysis demonstrated a significant reduction in the total abundances of ARGs and mobile genetic elements (MGEs) in soils amended with biochar compared to those treated with compost. This finding highlights the potential of biochar as an effective strategy for mitigating the spread of antibiotic resistance within agricultural ecosystems. Additionally, the biochar-treated plants exhibited upregulation of pathways related to plant-pathogen interactions, unsaturated fatty acid biosynthesis, fatty acid metabolism, tryptophan metabolism, *GnRH* signalling, and antigen processing and presentation (Zhu et al. 2021).

5.3 Proteomics analysis

Proteomic analysis, also referred to as proteomics, involves the systematic process of identifying and quantifying all the proteins present in a biological system at a specific condition (Al-Daffaie et al. 2024a, b; Pan et al. 2024). The metaproteomic examination of the microbial community in soils contaminated with 2,4-dichlorophenoxy (2,4-D) reveals that a minimum of two species are associated with the biodegradation of chlorobenzene. Furthermore, it was observed that 2,4-dichlorophenoxyacetate dioxygenase, which plays a role in the degradation of 2,4-D, is expressed by indigenous bacterial populations (Mishra et al. 2021). A recent study utilizing culture-dependent community proteomics investigated alterations in the microbial assemblages present in soil contaminated with organic pollutants. The findings indicated that the soil microbial community exhibits increased complexity in contaminated soils relative to untreated soil (Stefani et al. 2015). *Bacillus* sp. was prevalent in both communities, while other species, including *Ralstonia solanacearum, Synechococcus elongatus,* and *Clostridium* sp., were absent in the non-contaminated soil (Stefani et al. 2015). A subsequent investigation into the bioremediation of organic pollutants revealed that compost-assisted bioremediation was primarily facilitated by *Sphingomonadales* and uncultured bacteria. These microorganisms exhibited significant expressions of catabolic enzymes, including catechol 2,3-dioxygenase, *cis*-dihydrodiol dehydrogenase, and 2-hydroxymuconic semialdehyde dehydrogenase. A comparable metaproteomic analysis of toluene-amended soil and enriched cultures containing toluene and soil extracts indicated that numerous proteins are common between the two toluene-amended communities. In comparison to the glucose-amended soil serving as the control, there was a notable increase in the expression of glutamine synthetase, ABC transporters, extracellular solute-binding proteins, and outer membrane proteins within the toluene-amended communities, suggesting their potential role in the removal of toluene from bacterial cells (Williams et al. 2010).

5.4 Metabolomics analysis

Metabolomics involves the study of metabolome, which encompasses all the metabolites produced by cells (Rathore and Shakya, 2024). Li et al. (2023) observed that oil pollution markedly altered the composition of soil microorganisms and metabolites, leading to an increase in the relative abundance of organic pollutant biodegradation and metabolism. Another study analyzed the changes in the metabolome of ryegrass in petroleum hydrocarbon contaminated soil in presence of biochar and urea amendments. Results indicated that biochar and urea activated the putative petroleum hydrocarbon catabolic pathway, involving naphthalene and anthracene degradation (Li et al. 2020a, b, c, d, e, f). Another study highlighted the positive effects of sewage sludge biochar (SSBC) on wheat growth and its role in enhancing toxic tolerance processes. Metabolome analysis identified key pathways involved in the metabolism of proteins, fatty acids, and carbohydrates, and noted significant upregulation of glyoxylate and dicarboxylate metabolism, naphthalene and anthracene degradation, as well as butanoate, pyruvate, and glycolysis/gluconeogenesis pathways. This heightened metabolic activity facilitated a more efficient microbial response to petroleum hydrocarbons, resulting in a substantial 78.6% reduction of these contaminants in the soil (Kong et al. 2019). The combination of biochar and plant roots had a significant impact on the metabolism of sucrose and starch, leading to an enhancement in the diversity of soil metabolites which improves bacterial resilience to stress caused by PAHs and its elimination from the soil (Li et al. 2020a, b, c, d, e, f).

Similarly, Li et al. (2020a, b, c, d, e, f) conducted a root-box experiment using ryegrass in combination with maize-straw-derived biochar to examine the PAH degradation network and its integration with soil carbon cycling. The metabolomic analysis demonstrated that biochar application significantly upregulated upstream functional genes associated with PAH degradation, such as PAH dioxygenase large-subunit, estradiol-dioxygenase, aldehyde dehydrogenase, naphthalene 1,2-dioxygenase subunit alpha, 1,2-dihydroxy naphthalene dioxygenase, 2-hydroxy chromene-2-carboxylate isomerase, and trans-o-hydroxy benzylidene pyruvate hydratase-aldolase. Additionally, low-molecular-weight metabolites generated during the degradation of PAH (phthalate, benzoate, salicylaldehyde, and 4-hydroxy-benzoate) were incorporated into the soil carbon metabolic network, serving as carbon and energy substrates for microbial growth. The combined effects of biochar and plant roots modulated key downstream metabolic pathways, including that of carbohydrate, amino acid, and lipid metabolism (Shu et al. 2022; Badejo et al., 2014; Menezes et al., 2017). Lipid metabolism was identified as a microbial strategy to mitigate pollution stress (Shu et al. 2022), while amino acid metabolism, particularly glutathione metabolism, contributed to detoxification and stress tolerance within the rhizosphere (Badejo et al., 2014). Carbohydrate metabolism, essential for energy production and molecular transformation, was notably stimulated under the combined influence of biochar and rhizosphere interactions, counteracting the inhibitory effects of pollution and further facilitating efficient PAH degradation (de Menezes et al. 2017; Li et al. 2020a, b, c, d, e, f). Figure 4 illustrates the different applications of biochar in plant–microbe interactions, microbial organic contaminant degradation pathways and several omics approaches to determine the microbial community and metabolic pathways and their related genes.

6 Biochar production processes and advanced engineering strategies for enhanced degradation of organic pollutants

The production of biochar from diverse feedstocks relies on a range of thermochemical conversion processes, with pyrolysis, torrefaction, hydro-thermal carbonization, gasification, and flash carbonization being the most prominent methods (Muh et al. 2021; Singh Yadav et al. 2023). These thermochemical processes, in combination with engineering techniques, enable the manufacture of biochar with functional and beneficial attributes, which make it efficient for application in various environmental and industrial settings (Zou et al. 2022). Biochar engineering involves enhancing its substance adsorption capacity through physical, chemical, and morphological techniques (Whitman et al. 2015). These techniques can improve surface area, pore volume, aromaticity, oxygen-containing functional groups, and ion exchange capabilities (Chen et al. 2024). Physical techniques like gas and steam activation, pressure application, electrochemical processes, ultraviolet treatment, ultrasound, plasma exposure, and thermal treatment improve physicochemical properties (Sajjadi et al. 2019). Chemical alteration procedures, such as acids, metal salts, oxides, and alkalis, can be executed independently or combined with physical methods (Gao et al. 2023). Biological alteration of biochar can improve microbial or enzymatic activity on its surface (Kong et al. 2023a, b). Figure 5 shows the different biochar feedstocks and their preparation mechanism.

6.1 Biomass selection

The intrinsic properties of biomass significantly impact the production and characteristics of biochar through catalytic mechanisms during pyrolysis (300–900 °C) (Lee et al. 2022). Consequently, biomass with high lignocellulosic and non-lignocellulosic content exhibits distinct attributes in the resulting biochar (Elsaddik et al. 2024). The main sources of potential lignocellulose biomass for biochar formation include agronomic waste, wood leftovers, and forest biomass (Rangabhashiyam and Balasubramanian 2019). Such feedstocks are commonly utilized to produce nano-biochar (Bhandari et al. 2023), owing to its potential applications in carbon capture and storage, energy production, and the remediation of organic contaminants (agrochemicals, pharmaceuticals, and various inorganic and organic substances) (Senthil Rathi et al. 2024). The dominant constituents of these biomasses are cellulose (25–50 wt%), hemicellulose (15–40 wt%),

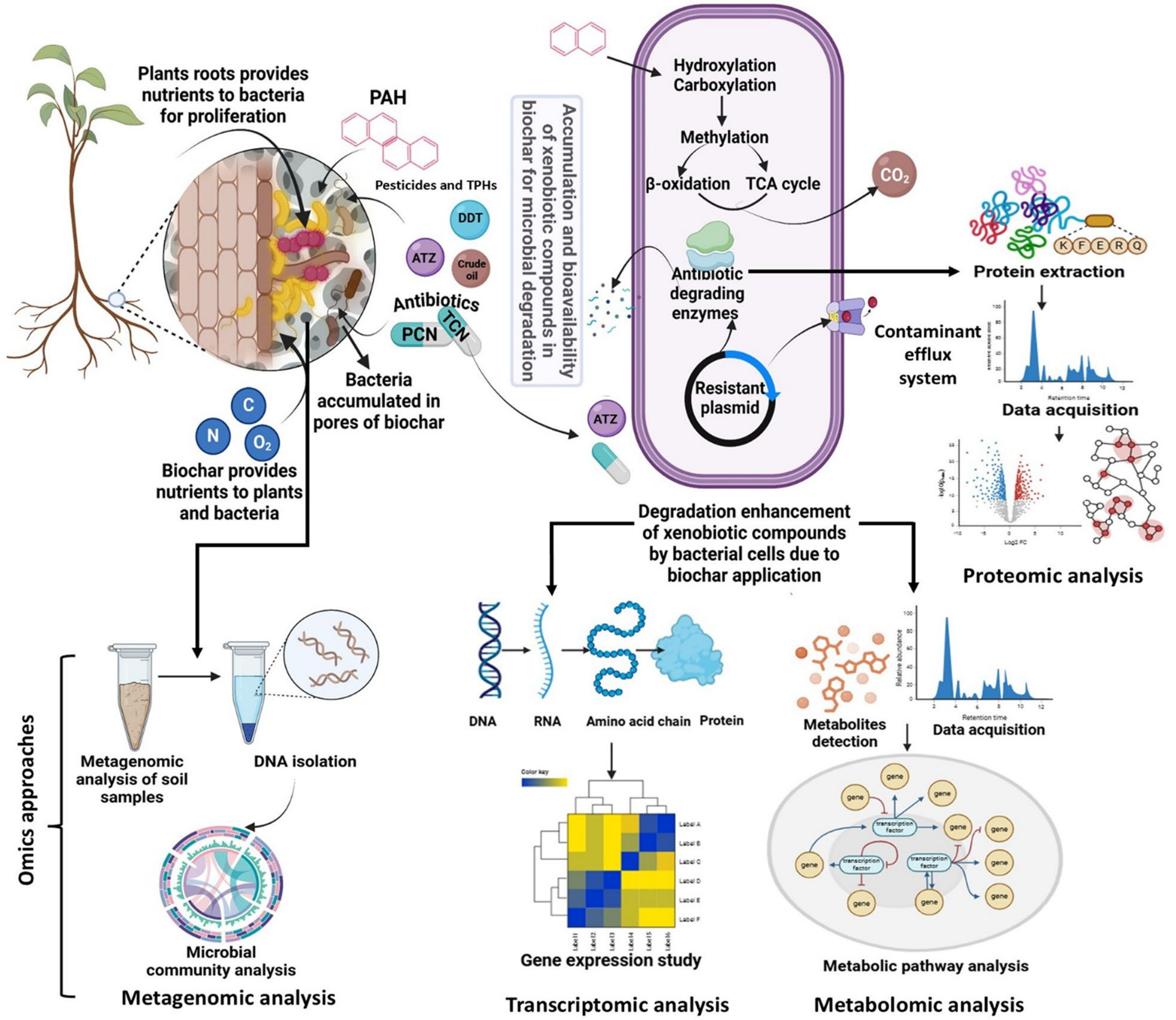


Fig. 4 Different applications of biochar in plant–microbe interactions, microbial organic contaminant degradation pathways and several omics approaches to determining the microbial community and metabolic pathways and their related genes

lignin (10–40 wt%), and minerals (1–15 wt%) (Deng et al. 2023). Cellulose is utilized for the removal of antibiotics, and other pharmaceutical pollutants from water and soil (Chandel et al. 2023). Chemical modifications to cellulose enhance adsorption capacity for contaminants, but source and extraction procedure significantly impact lignocellulosic biomasses' adsorption characteristics, hydrophilicity, functionality, and reactivity (Agustin et al. 2022; Kumar et al. 2024). Moreover, biochar produced from herbaceous and agro-industrial feedstocks showed the highest CO_2 capture efficiency at 600–700 °C, with sono-aminated *Miscanthus* and switchgrass achieving a 200% improvement due to large surface area (303–325 m^2 g^{-1}), high carbon content (82–84%), and low ash content (4–5%), optimizing its adsorption capacity (Chatterjee et al. 2019).

Nano-biochar obtained from oak wood exhibited a specific surface area of 305 m^2 g^{-1} and demonstrated effective adsorption of acetone, cyclohexane, chloroform, ethanol, and toluene, achieving an adsorption rate ranging from 23.4 to 103.4 mg g^{-1} (Sani et al. 2023). The biochar material subjected to ball milling demonstrated adsorption abilities of 100.3 and 57.9 mg g^{-1} over the elimination of the antibiotic sulfamethoxazole and sulfapyridine, respectively (Huang et al. 2020). Similarly, peanut shell nano-biochar treated with goethite showed enhanced hetero-aggregation and increased adsorption rates, and demonstrated 99.4% trichloroethylene removal

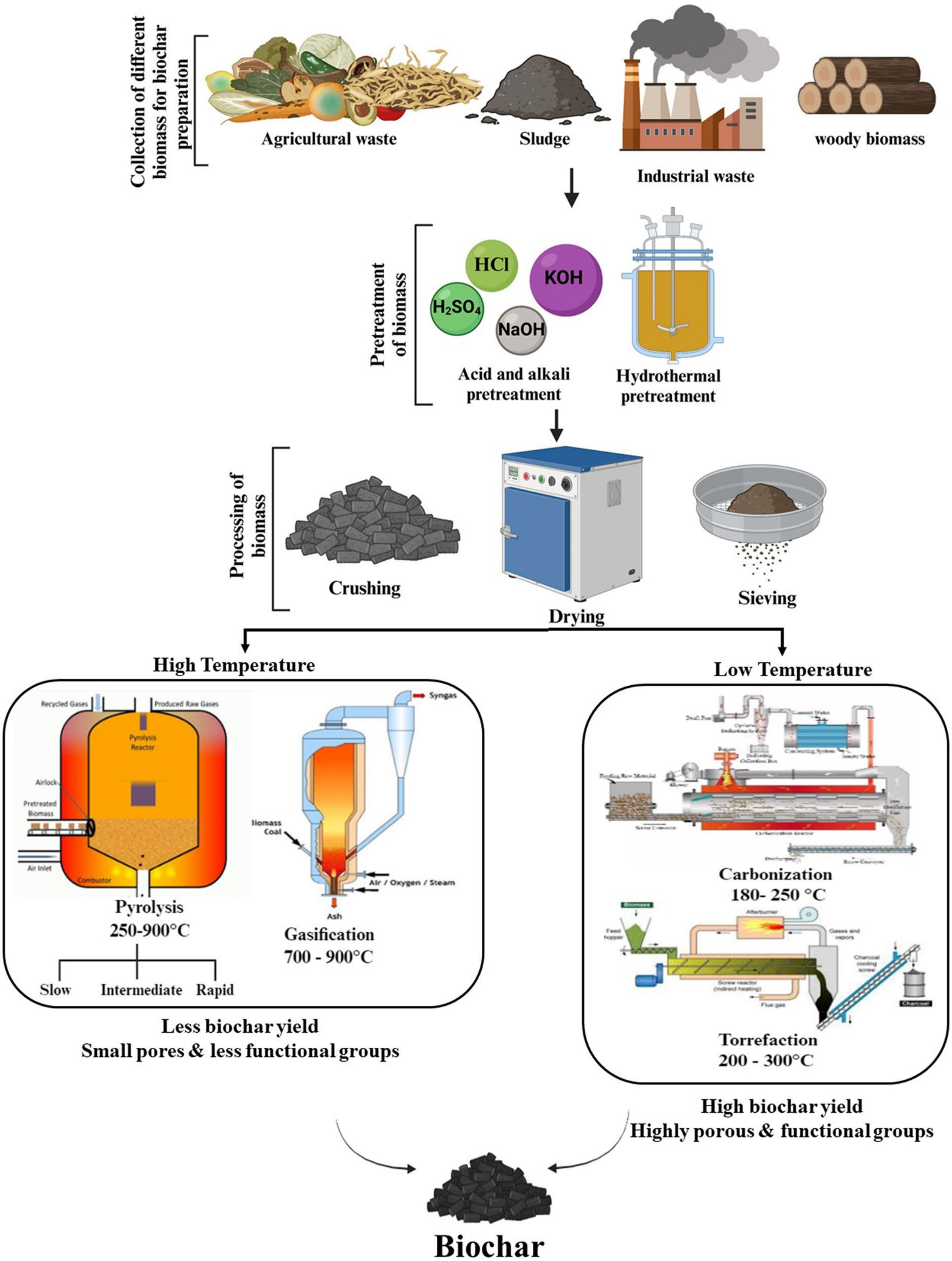


Fig. 5 Biochar production through several feedstocks, preparation processes and their mechanism of production

efficiency in just 5 min (Xiao et al. 2020). Additionally, the viability of supplying plants with slow-release basic micro and macronutrients was investigated using biochar-based nanocomposites generated from maize waste (Ghassemi-Golezani and Rahimzadeh 2022). Moreover, utilizing these biomasses for biochar production, which are otherwise lignocellulosic wastes, can contribute to achieving several SDGs goals, including Objective 3 (Optimal Health and Well-being), Objective 6 (Uncontaminated Water and Sanitation), Objective 7 (Affordable and clean energy), Objective 13 (Climate Action), and Objective 15 (Sustainable Life on Earth) (Chaubey et al. 2023). The detailed overview of biochar application, aligned to several SDG objectives, are listed in Table 4.

6.2 Effect of pyrolysis temperature on biochar for enhanced removal of contaminants

Pyrolysis is the thermal breakdown of organic substances in an oxygen-deprived atmosphere, specifically within the temperature range of 250–900 °C (Puppa et al. 2020). In addition to flash and vacuum pyrolysis, the pyrolysis process has been categorized into slow, intermediate, and rapid modes (Al-Rumaihi et al. 2022). Fast pyrolysis is a rapid thermal processing method used to rapidly pulverize biomass with a moisture level below 10%, maintaining temperatures between 850 and 1250 °C. Slow pyrolysis is distinguished by a significantly lower heating rate, typically around 5–7 °C/min, at temperatures ranging from 450 to 500 °C. Slow pyrolysis, a process with an extended residence time and gaseous vapor release, reduces harmful emissions, making it eco-friendly and beneficial for soil restoration and effluent adsorption (Harussani and Sapuan 2024; Zhang et al. 2018). High-temperature biochar offers several advantages, including a large surface area, high cation exchange capacity, and elevated pH levels. Rafiq et al. (2016), investigated the influence of pyrolytic temperatures on the carbon level in maize stover biochar, revealing that increasing temperatures lead to a rise in carbon content from 45.5 to 64.5%. The specific surface area analysis found that date palm biochar produced at 700 °C had an S_{BET} of 249.130 m^2/g, 122 times higher than biochar produced at 300 °C (S_{BET} = 2.04 m^2/g) (Elnour et al. 2019). High temperatures during pyrolysis enhances microporosity by releasing volatile compounds, opening surface centers, and creating new pores (Yaashikaa et al. 2020). Paul et al. (2024) reported that rice straw biochar, produced through thermal pyrolysis with $Fe(NO3)_3$, significantly adsorbs guaiacol, anisole, and phenol due to its larger pore volume and surface area (3–35 mg/L for 0.009 g of biochar). Zhang et al. (2023), utilized magnetic functionalized biochar (MF-BC) from rice trash to eliminate tetracycline antibiotics and achieved a 96.02% adsorption rate on the adsorbent surface. Additionally, the alkali-active porous biochar was prepared at a high temperature of 850 °C using corncob xylose residue, which showed adsorption capabilities of 1492 mg g^{-1} for sulfamethoxazole with a removal capacity of 98.52% (Li et al. 2022a, b).

However, when biochar is produced at lower temperatures with an oxygen concentration of 20%, it is crucial to enhance its properties by incorporating additional active sites and ensuring a stable carbon–oxygen structure. Moreover, one of the key characteristics of biomass feedstock is the moisture content, which influences bio-char synthesis (Tomczyk et al. 2020). Thus, the importance of maintaining low moisture content in biomass is preferred for biochar production (Das et al. 2021a, b; Yaashikaa et al. 2020). Mohamed et al. (2021) reported that biochar produced from microwave pyrolysis (300 °C) using switchgrass biomass with K_3PO_4 exhibited a robust negative net global warming potential (GWP) ranging from 159 to 223 kg CO_2-eq/1000 kg. However, slow pyrolysis, at a low heating rate, proved to minimize the need for secondary pyrolysis and thermal cracking, thereby maximizing the formation of biochar as the primary product (Tan et al. 2023). Zhang et al. (2020) studied the biochar made from rice straw pyrolyzed at 600 °C achieved biodegradation rates ranging from 40.00% to 58.84% for some PAHs with 3–6 rings. Similarly, Yoon et al. (2021) evaluated grape pomace biochar (GP-BC) produced at 350 °C with a surface area of 0.25 m^2 g^{-1}, an H/C ratio of 0.905, 1.94% K content, and an adsorption capacity for cymoxanil (CM) of 161 mg g^{-1}. Similarly, low-temperature sugarcane biochar achieved ~ 70% thiamethoxam removal within 60 min.

6.3 Gasification methods for enhanced removal of contaminants

Biomass gasification is a technique involving the partial oxidation of biomass at elevated temperatures, typically ranging from 700 to 900 °C (Giglio et al. 2021). The gasification procedure yields a mixture of products, including 10% biochar, 5% bio-oil, and 85% syngas (Adeniyi et al. 2024). In general, the gasification process involves four sequential stages: drying, pyrolyzing, partially oxidizing, and reducing (Alves et al. 2023; Chhiti et al., 2013). Biochar generated through gasification at temperatures above 500 °C is usually non-polar and aromatic since it has loose functional groups having oxygen and hydrogen (Canché-Escamilla et al. 2022). This property enhances its effectiveness in removing organic contaminants via sorption (Ahmad et al. 2014). A significant removal of trichloroethylene was achieved using soybean stover biochar produced at 700 °C (Ahmad et al. 2014). Compared to pyrolyzed biochar, gasification char typically has smaller particle sizes. Although gasification chars

Table 4 Overview of biochar application aligns with several SDG objectives

SI No.	SDG goals	Global scenario	Application of biochar	Related studies	References
	SDG 3: Ensure healthy lives and promote well-being for all at all ages Target 3.9: By 2030, substantially reduce the number of deaths and illnesses from hazardous chemicals and air, water and soil pollution and contamination	Globally 24% of all estimated deaths are linked to the environment 3.2 million deaths every year as a result of exposure to indoor smoke from cooking fuels 99% of the world's population live in places where air pollution levels exceed WHO guideline limits	Biochar amendments have been used to mitigate soil contamination by adsorbing and immobilizing pollutants, including heavy metals, organic compounds, and nutrients	• BC derived from bio-energy industries, Embilipitya (EBC), Mahiyanganaya (MBC), and Cinnamon Wood Biochar (CWBC) resulted rapid oil removal of 1.12 g kg^{-1} within 30 min • Biochar derived from oak leaves combined with mycorrhizae reduced 56% TPH from soil in the presence *Trifolium arvense* plants • The combined waste-fungus-chaff-biochar (WFCB) and *Herbaspirillum huttiense* immobilized Cu (85.5%) and Zn (64.4%) while degrading oxytetracycline (41.9%) and enrofloxacin (40.7%)	Pallewatta et al., (2023); Abbaspour et al., (2020); Zhang et al., (2022)
	SDG 6: Ensure availability and sustainable management of water and sanitation for all Target 6.3: By 2030, improve water quality by reducing pollution, eliminating dumping and minimizing release of hazardous chemicals and materials, halving the proportion of untreated wastewater and substantially increasing recycling and safe reuse globally	In 2008, 900 million people lacked access to improved drinking water By 2015, over 2.4 billion people lacked improved sanitation facilities 1.8 billion people depend on tainted drinking water Over 80% of human-generated wastewater is released into rivers or oceans without pollution treatment Water-related diseases cause 1.8 million deaths annually, causing 2.2 million deaths annually from diseases like cholera, typhoid, and dysentery	The porous structure of biochar, along with its microbial activity, offers benefits for water filtration and purification Biochar, an eco-friendly adsorbent with a low charge, is derived from biomaterials and is suitable for use in economically disadvantaged regions	• Rice husk-derived BC, modified with ferric oxide nanoparticles, demonstrated a removal efficiency of 99.8% for U (VI) from water at an initial concentration of 3 mg/L • BC derived from maize stalks, *Lantana camara,* pine needles, and black gram feedstock removed 78.5–86.5% of heavy metals from wastewater at a municipal treatment plant • BC derived from poplar sawdust achieved removal rates of 9.01% for Pb^{2+} and 7.53% for Cd^{2+} at initial concentrations of 200 mg/L	Sen et al., (2021); Thakur et al., (2022); Cheng et al., (2022)

Table 4 (continued)

SI No.	SDG goals	Global scenario	Application of biochar	Related studies	References
	SDG 7: Ensure access to affordable, reliable, sustainable and modern energy for all Target 7.a: By 2030, enhance international cooperation to facilitate access to clean energy research and technology, including renewable energy, energy efficiency and advanced and cleaner fossil-fuel technology, and promote investment in energy infrastructure and clean energy technology	Global energy consumption grew by 2.2% in 2023, driven by BRICS nations (+5.1%), with China (+6.6%) and India (+5.1%) leading the surge Global oil demand is projected to reach 103 million barrels per day (mb/d) in 2024	Biochar, with its high acid density, large surface area, catalytic activity, and reusability, achieves an esterification efficiency of 90–100% as an acid catalyst. The strong thermal stability (up to 600 °C) enhances the pyrolysis of plastic waste, producing higher-quality liquid oil by removing contaminants. The porous structure aids in reducing greenhouse gas emissions and converting CO_2 into fuels	• Biochar application significantly reduces GHG emission (2–19 Mg CO_2 ha^{-1} y^{-1}), with 41–64% attributed to biochar's carbon retention and the rest to fossil fuel offsets, fertilizer savings, and avoided soil emissions. 30% reduction in energy output, biochar-enhanced systems achieve higher energy efficiency (2–7 MJ/MJ) compared to corn ethanol. Biochar application reduces lifecycle emissions for electricity production (91–360 kg CO_2 MWh^{-1}), far below fossil fuel emissions (600–900 kg CO_2 MWh^{-1}) • Wood-based biochar (BCp, BCc) used as microbial fuel cell electrodes deliver competitive power outputs (532 ± 18 mW m^{-2}, 457 ± 20 mW m^{-2}) at significantly lower costs (17–35 US\$ W^{-1}), reducing carbon footprint and offering agronomic disposal benefits • Activated carbon from coffee waste achieved a power density of 3927 mW/m^2, outperforming commercially available activated carbon (975 mW/m^2)	Gaunt & Lehmann, (2008); Huggins et al., (2014); Hung et al., (2019)

Table 4 (continued)

SI No.	SDG goals	Global scenario	Application of biochar	Related studies	References
	SDG 13: Takeurgent action to combat climate change and its impacts Target 13.1: Strengthen resilience and adaptive capacity to climate-related hazards and natural disasters in all countries	Since 1850, the average annual rise in land and ocean temperatures has been 0.11° Fahrenheit (0.06° Celsius) every decade, or almost 2° F overall Since 2000, the number and duration of droughts has risen 29% In 2023, global average sea level set a new record high—101.4 mm (3.99 inches) Antarctica is losing ice mass (melting) at an average rate of about 150 billion tons per year, and Greenland is losing about 270 billion tons per year, adding to sea level rise	Biochar systems have the potential to decrease global emissions by 3.4–6.3 PgCO_2e, with 50% of these reductions attributed to CO_2 removal. Notably, emissions rise by 3% when coal is replaced, whereas a substantial reduction of 95% occurs when renewable energy sources are substituted The application of biochar in soil enhancement contributes to the mitigation of emissions such as N_2O, CO_2, and CH_4	• The annual production of 300 tons of biochar could contribute to the sequestration of 0.5 billion tons of CO_2, roughly 1.5% of global annual CO_2 emissions • It is estimated that biochar, containing 78% carbon, could store between 7 and 110 gigatons of carbon with a maximum application rate of 100,000 kg per hectare across 1411 million hectares of cropland • The application of a combination of slag and biochar (8 + 8 tons ha^{-1}) in a paddy field resulted in a 45% reduction in CH_4 emissions • The biochar-containing constructed wetland system reduced N_2O and CH_4 global warming potential by 18.5% and 24%, respectively. Biochar production from a 100 tons/day sludge WWTP could capture 21 K_{eq} of CO_2, reducing 0.9 kg of GHG emissions per kg of biochar	NOAA's Annual Climate Report, (2023); Lathwal et al., (2023); Chen et al., (2022); Karki et al., (2024)

Table 4 (continued)

SI No.	SDG goals	Global scenario	Application of biochar	Related studies	References
	SDG 15: Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss Target 15.3: By 2030, combat desertification, restore degraded land and soil, including land affected by desertification, drought and floods, and strive to achieve a land degradation-neutral world	From 2015 to 2019, at least 100 million hectares of productive land were degraded annually, affecting 1.3 billion people. Agricultural expansion directly caused nearly 90% of deforestation	Biochar's high surface area, porosity, and oxygen-rich functional groups make it ideal for soil and water remediation, supporting SDG 15 for life on land It improves soil fertility, structure, electrical conductivity (EC), cation exchange capacity (CEC), and nutrient retention	• Wheat straw biochar pyrolyzed at 500 °C achieved 83.7% soil contamination removal efficiency from 8 ppm due to enhanced surface area, pH, porosity, and surface functional groups • The incorporation of wheat straw and sludge composite biochar into Cu and Pb-contaminated soil resulted in a reduction of contamination levels by 36.81% for Cu and 25.61% for Pb • BC enhanced the cation exchange capacity (CEC), pH, and soil organic carbon by 20%, 46%, and 27%, respectively. BC improved soil quality and lentil growth by enhancing CEC, organic carbon, and available potassium, while reducing bulk density • The combination of BC with N&P fertilizers boosted crop yield, indicating that BC can significantly improve fertilizer use efficiency	Tang et al., (2022); Kumar and Bhattacharya (2022); Wang et al., (2023); Abrishamkesh et al., (2015)

have a lower carbon content, ranging from 20 to 60 wt%, their stability is enhanced by the presence of condensed aromatic rings, which confer significant resistance to chemical oxidation and microbial mineralization (You et al. 2017; Fryda and Visser 2015). Although, their surface structure is limited due to the reduced number of functional groups. The gasification of straw and wood is often performed through a two-stage process that separates pyrolysis and gasification into distinct reactors, operating at approximately 730 °C (You et al. 2018; El-Shafay et al. 2019). This method produces chars with high porosity and a specific surface area of 418 m^2g^{-1}, making them promising candidates for soil restoration (Amer et al. 2024). According to Azeem et al. (2023), the introduction of microorganisms with biochar facilitates their higher rates of survival, which in turn improves the integration and growth of microorganisms within the soil and the plant root zone. The self-immobilization technique facilitated the attachment of *Arthrobacter* sp. ZXY-2 and *Aspergillus niger* Y3 onto charcoal, leading to a notable enhancement in the removal of atrazine via both adsorption and degradation mechanisms. Ha et al. (2022) utilized cell-immobilized biochar techniques to immobilize *Pseudomonas putida* onto coconut shell fiber biochar, with the aim of effectively adsorbed Paraquat at a rate of 16.79 mg g^{-1} in 48 h, and remove 95.79% of Paraquat from water with a concentration of 30 mg L^{-1}. Similarly, Xiong et al (2017) showed that a composite of *Mycobacterium gilvum*-modified rice-straw biochar was more effective in breaking down soil PAHs compared to unmodified biochar.

6.4 Torrefaction methods for enhance contaminant removal

Torrefaction involves the thermal degradation of organic matter in a nitrogen or other inert atmosphere, typically at temperatures between 200 and 300 °C (Eling et al. 2024). Torrefaction can be categorized into two types based on the characteristics of biomass: dry and wet processes (Yang et al. 2024). In dry torrefaction, biomass undergoes controlled heating in an oxygen-free environment, such as N_2 or CO_2. This method leads to partial degradation rather than combustion, enhancing the resistance of biomass to temperature fluctuations and its ability to absorb water vapor (Tumuluru et al. 2021; Chen et al. 2021). In contrast, wet torrefaction involves controlled heating of the material in hot water or steam at high pressures, resulting in partial degradation (Çetinkaya et al 2024). Generally, dry torrefaction requires higher temperatures (200–300 °C) compared to wet torrefaction (150–260 °C) (Bach et al. 2016). The solid product generated through torrefaction is typically carbon-enriched, porous, and characterized by low density (Mukhtar et al. 2023). It also exhibits a reduced oxygen-to-carbon ratio and moisture content, along with a higher energy density, storage and transportation (Kuwata et al. 2012). De Jesus (2017) showed torrefied biomass materials from coconut and orange waste, which were able to eliminate BkF (benzo[k]fluoranthene), B[a]A (benzo[a]anthracene), BbF (benzo[b]fluoranthene), B[a]P (benzo[a]pyrene), and DBahA (dibenzo[a,h]anthracene) from a solution, ranging from 47.09% to 83.02% and 23.84–84.02%, respectively.

6.5 Hydrothermal carbonization methods for enhanceing contaminant removal

Hydrothermal carbonization is widely recognized as a highly efficient technique for producing biochar due to its ability to operate at temperatures that are comparatively low, generally between 180 and 250 °C (Seow et al. 2022). According to Pavkov et al. (2022), hydrothermal carbonization is achieved by dissolving biomass sources in water in a hermetically sealed system, which is subsequently heated to 300 °C for around 16 h. Under the specified operating conditions and in the presence of water, biochar is formed with a higher concentration of oxygen-containing functional groups (OFGs). Hydrothermal carbonization is a natural process that simultaneously releases thermal energy, resulting in the incorporation of carbon from the starting material into the final product called hydrochar (Zhao et al. 2018; Wang et al. 2018a, b). Flash carbonization is a highly efficient method of producing biochar compared to traditional carbonization techniques. It offers a significant increase in biochar yield (28–32%) and a remarkably short reaction time of just 30 min (Lee et al. 2024). Hou et al. (2022) reported that biochar carbonized at 800 °C had an optimal balance of adsorption capacity, reaction kinetics, and recyclability, with a surface area of 693 m^2 g^{-1} and a maximum removal capacity of 449 mg g^{-1}.

Liu et al. (2014) observed that the adsorption capacity of hydrochar for triclosan and tetracycline was markedly improved by the alkali activation of a magnetized hydrochar composite containing iron oxide. The main categories of biochar composites consist of nano zero valent iron (nZVI)-biochar, iron oxide-biochar, and iron sulphide-biochar composites. The combination of iron and biochar composites enhanced the process of adsorption and immobilization of organic contaminants by improving surface complexation, precipitation, and electrostatic interactions (Shaheen et al. 2022). Iron-biochar composites, including nZVI-biochar and FeS-biochar, demonstrated an enhanced capacity for the reduction of organic pollutants as a result of their capability to produce Fe(0), Fe(II), and S(II) species (El-Naggar et al. 2022).

In another study, biochar modified with magnesium (Mg) and the biosurfactant rhamnolipid (RL) demonstrated a substantial ability to adsorb phosphate, with a capacity of 118 mg g^{-1}, and significantly reduced TPH with an adsorption capacity of 44.4 mg g^{-1} (Wei et al. 2023). Zhang et al. (2023) utilized magnetic functionalized biochar (MF-BC) from rice trash, which showed absorption of tetracycline by 96.02%. Additionally, the alkali-active porous biochar was prepared at a high temperature of 850 °C using corncob xylose residue, which showed adsorption capabilities of 1492 mg g^{-1} for sulfamethoxazole, with a removal capacity of 98.52% (Li et al. 2022a, b). Nevertheless, cobalt-gadolinium-modified biochar, derived from *Camellia oleifera* shells, with a surface area of 169.79–370.73 m^2 g^{-1} and a pore volume of 0.09–0.199 cm^3 g^{-1}, proved to be a highly effective solution for addressing ciprofloxacin and tetracycline contamination (Oni et al. 2019). The utilization of an iron oxide-biochar composite reduced chlorpyrifos uptake by *Allium fistulosum* (Welsh onion) and enhanced atrazine breakdown by *Acinetobacter lwoffii* DNS32, leading to the production of biofilms on iron biochar composites (Tang et al. 2022; Tao et al. 2019). Magnetic biochar demonstrates the capacity to efficiently remove various organic contaminants, including pesticides, phenols, organochlorines, and hormones, with adsorption capabilities ranging from 3.46 mg g^{-1} to 169.7 mg g^{-1} (Qu et al. 2022). Figure 6 depicts different functional and beneficial attributes of engineered biochar. Application of modified biochar for removal of different contaminants is listed in Table 5.

7 Ecotoxicological impact and challenges of biochar application in organic pollutants remediation process

Concerns have been raised regarding the presence of metals and aromatic compounds in biochar, emphasizing the need to integrate chemical analysis with ecotoxicological evaluation. This is particularly important given the limited information available on the ecotoxicological impact of biochar in contaminated soil. Although the use of biochar demonstrates efficacy in soil remediation, its application within the soil presents certain challenges. The application of biochar to soil can lead to nitrogen and nutrient immobilization due to its elevated carbon to nitrogen (C:N) ratio, which is a consequence of the substantial carbon content present in biochar. The elevated carbon-to-nitrogen ratio was documented by García-Delgado et al. (2015), as a contributing factor to the limited growth of bacterial and fungal populations, which in turn affects the degradation of PAHs. The observed imbalance in the carbon to nitrogen ratio can be increased through the addition of nitrogen to biochar treatments, potentially leading to improved TPHs removal (Saum et al. 2018). Other researchers have observed that the removal of TPH was more pronounced in soil treated with both biochar and nutrients, compared to cases where biochar was applied alone (Lawson et al. 2019; Wang et al. 2017a, b; Wei et al., 2023). Kuppusamy et al. (2017) highlighted the potential risk of heavy metals and PAHs leaching from biochar into the soil after its application. In contrast, Freddo et al. (2012) suggested that the environmental impact of biochar is likely minimal, as their findings indicated that the concentrations of PAHs, metals, and metalloids were below the acceptable limits for sewage sludge and either lower than or within the regulatory limits for compost. However, it is important to exercise caution when considering this conclusion, as the biochar studied was derived from feedstock deemed less toxic (Freddo et al. 2012).

Therefore, it is recommended that before applying biochar to soil, its physicochemical properties should be carefully considered, as it may contain hazardous substances such as heavy metals and organic pollutants (Li et al. 2018). Furthermore, the presence of VOCs in biochar used on soil can have negative effects on microorganisms. The presence of VOCs in biochar can be influenced by the pyrolysis temperature used during production. Further, higher temperatures (300–600 °C) tend to volatilize these compounds, while some semi-volatilized organic compounds may still be retained in the biochar (Lian and Xing 2017). PAHs are produced when biomass is incompletely combusted. However, if the pyrolysis conditions are appropriate, the production of biochar can help decrease the levels of PAHs. Additionally, the process of biochar pyrolysis leads to the formation of a unique type of environmental pollutant called environmental persistent free radicals (EPFRs) (Bi et al. 2022). EPFRs are radicals containing oxygen that are produced during the pyrolysis of biochar. Thus, it is essential to implement appropriate precautions, to minimize the production of secondary contaminants during the pyrolysis process of biochar.

8 Conclusion and future perspectives

Rhizoremediation has been recognized as an effective natural strategy to address environmental pollution, mitigate climate change and restore ecosystem functionality (Su et al. 2022). The amendment of biochar offers significant potential to influence the rhizoremediation process particularly through its effects on the sorption/desorption dynamics, biodegradation, and leaching of contaminants (Hale et al. 2015). Despite the potential role of biochar as a tool for rhizoremediation, the full scope of biochar impact on microbial community composition in organic pollutants contaminated

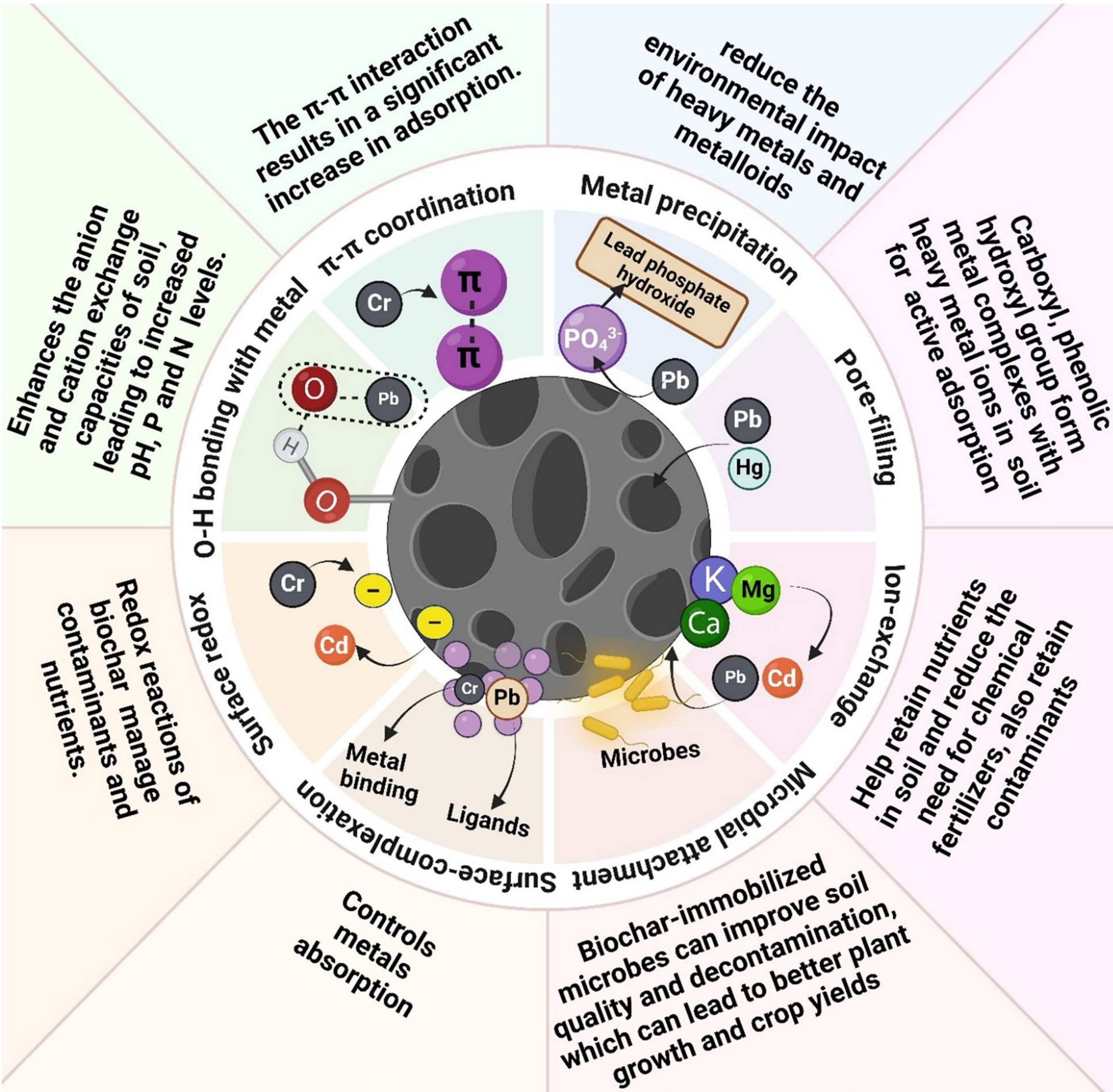


Fig. 6 Different mechanisms of biochar engineering and their beneficial attributes towards environmental clean-up

soils require more research. Existing studies indicate that biochar can improve soil physiochemical properties, enhance microbial activity, and promote biodegradation. Nonetheless, these studies are predominantly limited to controlled laboratory environments or green house setting, which need to be validated for their applicability to real world scenario. Field studies addressing the long-term effect of biochar amendments on rhizoremediation of contaminated are limited, leaving critical knowledge gaps regarding the stability and efficiency in diverse environments.

Furthermore, while engineered biochar offers several advantages for environmental applications and circular economy applications, its production and implementation face significant challenges. These include the optimization of manufacturing methods to enhance sustainability, ensuring its cost effectiveness and mitigating potential environmental risks associated with its application. Moreover, the successful advancement of biochar-based circular economy technology depends significantly on collaborative research efforts involving producers, consumers, and policymakers to overcome

Table 5 Application of modified biochar for removal of different organic contaminants

Contaminants	Biomass	Pyrolysis	Modifications	Absorbance rate (mg g^{-1})	References
Pesticides					
Carbaryl	Cow manure	600	HCl/HF	55 mg g^{-1}	Li et al., (2017)
Phenoxyacetic acid	Corn cob	600	HF	3.802 mg g^{-1}	Binh, and Nguyen, (2020)
Metolachlor	Walnut shell powder	700	Citric acid	74.07 mg g^{-1}	Liu et al., (2021)
Metribuzin	Switchgrass	425	Magnetic	205 mg g^{-1}	Essandoh et al., (2017)
Metolachor	Bagasse	500	Fulvic acid	99 mg g^{-1}	Liu et al., (2021)
Dichlorvos	Coconut fiber	600	HCl	90 mg g^{-1}	Essandoh et al., (2017)
		PAHs and crude oil			
Phenanthrene	Rice husk-derived	500	Nitric acid oxidation (RBO)	3.819 mg g^{-1}	Geng et al., (2024)
Benzo[b]fluoranthene	Constructed wetlands	500	Iron-modified	20.4%	Kang et al., (2023)
Pyrene	Rice hull biochar	500	β-cyclodextrin and chitosan	64.22%	Lin et al., (2024)
Dibenzo[a,h]anthracene	Wheat straw	600	Iron (Fe)-loaded	33.48%	He et al., (2023)
Phenanthrene	Rice straw, wood and bamboo	300–700	HCl	87.4%–131%	Feng, & Zhu, (2018)
Crude oil	Sugarcane-bagasse	300–700	Chitosan-biochar	45.82%	Liu et al., (2023)
Crude oil, diesel oil, and engine oil	Cornstalk biochar (CSBC)	350	Magnetic and silane agent modifications	8770 mg g^{-1}, 4010 mg g^{-1}, 4440 mg g^{-1}	Sun et al., (2022)
Crude oil	Rice husk	700	Rhamnolipid	32.9%	Zhen et al., (2021)
TPH	Coconut shell	600	Biochar/graphite carbon nitride (BC/g-C_3N_4)	54.5%	Lin et al., (2022)
TPH	Wheat stalk	400	$MgCl_2$	48.50%	Li et al., (2017)
	Antibiotics				
Tetracycline	Camellia oil shell	700	Sulfamic acid	412.95 mg g^{-1}	Liu et al., (2021)
Tetracycline	Coffee grounds	500	NaOH	39.22 mg g^{-1}	Nguyen et al., (2021)
Clomazone	Grapevine	350	H_2O_2	35.4%	Gámiz et al., (2019)
Cyhalofop, clomazone	Grapevine	900	H_2O_2	99%	Gámiz et al., (2019)
Ciprofloxacin hydrochloride	Rice straw biochar	60	Nanoscale Zero-Valent Iron particles (WS-NZVI)	363.63 mg g^{-1}	Shao et al., (2018)

these barriers. Such collaboration is essential to drive innovation, address existing research gaps, and refine biochar-based technologies for the effective and sustainable application of biochar in the future. Given the evolving market conditions, it is crucial to focus on enhancing biochar research, fostering innovation, and promoting its production.

The relationship between the biochar and rhizospheric microbiome is a complex phenomenon, while advanced omics technologies provided valuable insights related to microbial community dynamics. However, there is a need for more comprehensive research focusing on the bacterial community response, enzymatic activity and functional gene expression associated with biochar application. Advanced DNA technologies such as stable isotope probing (SIP) could also be used, which is a powerful tool offering deeper insights for specific microbial populations involved in rhizoremediation process in synergy with biochar applications.

Finally, the limited number of *in-situ* studies evaluating the long-term impacts of biochar amendments in organic pollutants -contaminated ecosystems underscores a critical research gap. Addressing this requires shifting the focus from short-term laboratory studies to robust field trials that assess biochar's environmental and functional efficacy over extended period. These efforts will be essential in determining the practicality and sustainability of biochar as a rhizoremediation tools in diverse environmental settings. In conclusion, the use of biochar, engineered and meticulously designed for the rhizoremediation of complex organic pollutants -contaminated soil, holds immense potential as a sustainable technology for eco-restoration. Its application offers significant prospects for promoting environmental recovery and advancing sustainable practices.

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Author contributions
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Data availability
The datasets used or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

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

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