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ADVANCES IN PYROGENIC CARBON: BRIDGING MOLECULAR MECHANISMS, ENGINEERED BIOCHAR PROCESSES, AND PLANETARY SCALE ENVIRONMENTAL IMPACTS-A REVIEW

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ABSTRACT
Pyrogenic carbon (PyC), particularly in the form of biochar, has emerged as a critical component in sustainable agriculture and climate change mitigation due to its unique physicochemical properties and long-term stability in soils. This review provides a critical synthesis of next generation pyrogenic carbon, integrating insights from molecular scale mechanisms to planetary scale environmental impacts. The formation of condensed aromatic carbon structures during thermochemical conversion processes such as pyrolysis, gasification, and hydrothermal carbonization underpins the remarkable persistence of PyC in soil systems. Interactions between pyrogenic carbon and soil minerals, along with limited microbial accessibility, further enhance its resistance to degradation. Recent advancements in Engineered biochar (EB) have significantly improved their performance in nutrient retention, contaminant remediation, and soil fertility. Modified biochar incorporating metals, minerals, and nanomaterials exhibits enhanced adsorption, ion exchange, and catalytic properties, enabling efficient immobilization of heavy metals and degradation of persistent organic pollutants. In agricultural systems, engineered biochar accelerates soil physical, chemical, and biological properties by increasing porosity, cation exchange capacity, nutrient availability, and microbial activity, while reducing nutrient leaching losses. Despite extensive research on biochar production, remediation performance, and soil applications, a critical unresolved question remains: how do molecular scale stabilization mechanisms translate into field scale persistence and ultimately influence planetary scale carbon cycling? This review addresses this question through a cross scale synthesis framework integrating molecular chemistry, soil ecological processes, environmental engineering applications, and climate mitigation outcomes.

KEYWORDS: Carbon Sequestration; Contaminant Remediation; Engineered Biochar; Nutrient Retention; Pyrogenic carbon (PyC)

1. INTRODUCTION

Pyrogenic carbon (PyC) is a thermally altered form of organic carbon produced during incomplete combustion or pyrolysis of biomass. Among the various forms of pyrogenic carbon, biochar has received significant attention due to its potential applications in agriculture, environmental remediation, and climate change mitigation. Biochar is typically produced by heating biomass residues such as crop straw, wood chips, manure, and agricultural wastes under oxygen limited conditions. The resulting material is characterized by high aromatic carbon content, large surface area, porous structure, and strong resistance to microbial decomposition.

Interest in biochar has grown rapidly over the past two decades as researchers have recognized its dual role in improving soil quality and mitigating greenhouse gas emissions. When applied to soils, biochar can enhance important soil properties such as water holding capacity, nutrient retention, soil aggregation, and microbial activity. These improvements contribute to increased crop productivity and enhanced soil health, particularly in degraded or nutrient poor soils (1). A key feature of biochar is its long-term stability in soil environments. The carbon present in biochar consists mainly of condensed aromatic structures formed during the pyrolysis process. These structures are highly resistant to microbial degradation and can persist in soils for decades or even centuries. As a result, biochar represents an effective long-term carbon sequestration strategy, capable of removing carbon dioxide from the atmosphere and storing it in soils.

In addition to its carbon sequestration potential, the production of biochar from agricultural residues can help reduce open biomass burning, thereby decreasing emissions of black carbon and other atmospheric pollutants, with biochar schemes can reduce global warming potential including black carbon by 2.46 to 3.22 times compared to open burning (2). Open field burning of crop residue contributes significantly to greenhouse gas emissions and air pollution, a challenge that may be addressed by producing biochar through the pyrolysis of agricultural crop residues (3). Recent advances in biochar research have moved beyond conventional soil amendments toward the development of engineered biochar with enhanced functionality. Engineered biochar (EB) are promising candidates in a wide range of environmental applications, including soil fertility improvement, contaminant immobilization, wastewater treatment, and in situ carbon sequestration with metals, minerals, layered double hydroxides, carbonaceous nanomaterials, and microorganisms enhancing biochar (4). Incorporating nanomaterials significantly enhances the adsorptive and reactive properties of biochar, supported by metal nanoparticles showing promise in removing heavy metals, organic contaminants, and other inorganic pollutants from aqueous environments, soil, and air (5).

Given the increasing importance of biochar in sustainable agriculture and climate mitigation strategies, there is a need to integrate knowledge from molecular mechanisms to global scale environmental impacts. While numerous reviews have addressed specific dimensions of biochar science including production methods, soil amendments, and contaminant remediation few have systematically integrated molecular scale stability mechanisms with planetary scale carbon cycling implications. A critical gap persists in translating laboratory derived persistence estimates into reliable field scale predictions, with recent evidence suggesting that field mineralization rates may exceed laboratory estimates by one to two orders of magnitude. This review addresses this gap by synthesizing evidence across scales, from the formation of condensed aromatic networks during thermochemical conversion, through engineered functionalization strategies and soil microbe biochar interactions, to global carbon budgets and circular bioeconomy frameworks.

2. MATERIALS AND METHODOLOGY

This critical review was conducted using a systematic and reproducible literature search framework to identify, evaluate, and synthesize evidence on advances in pyrogenic carbon spanning molecular level stabilization mechanisms, engineered biochar functionalization strategies, soil application outcomes, and planetary scale carbon cycling implications. The methodology integrates a structured bibliographic database search, a rigorous article screening process, quality appraisal criteria, and a bibliometric co-occurrence analysis to map the thematic landscape of the field. No primary experimental data were generated; all findings are derived from synthesis of published peer reviewed literature.

2.1 Trend Analysis of Research Output

To quantify and contextualize the growth of the pyrogenic carbon and engineered biochar research field, a trend analysis of annual publication output and cumulative citation frequency was conducted using the Scopus database. Data were retrieved using the combined keyword string "engineered biochar" AND "contaminant remediation" and restricted to the period 2016-2026. Annual publication counts and citation records were extracted and are presented graphically in Fig.1.

The trend analysis reveals a non-linear trajectory in both publication volume and citation frequency over this period, rather than sustained growth. Publication output peaked early, in 2017, followed by a sharp decline and a modest secondary rise in 2019-2020, after which both publications and citations declined progressively through 2026. Citation activity peaked slightly later than publications, in 2019-2020, before following a similar downward trend. This pattern suggests that research interest in engineered biochar as a multifunctional environmental and agricultural material was strongest in the late 2010s, coinciding with growing recognition of biochar's role in circular bioeconomy frameworks and its potential as a negative emissions technology but has since contracted, indicating either a maturing research area or a shift of attention toward related emerging topics not fully captured by the search terms used here.

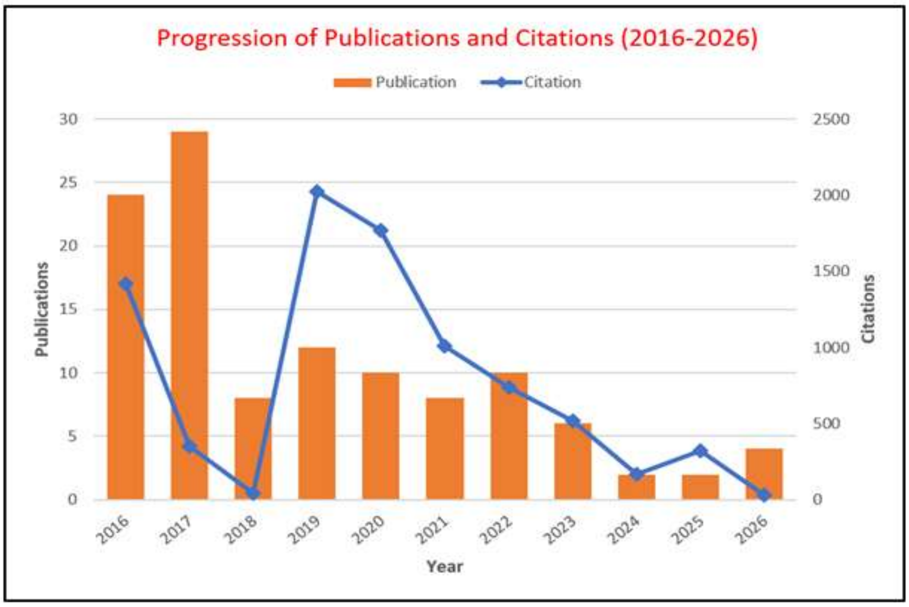

Fig.1. Trend Analysis of Biochar Research: Publications and Citations between 2016-2026 (Keywords: engineered biochar + Contaminant Remediation; Data from the SCOPUS database)

2.2 Bibliometric Keyword Co-occurrence Analysis
A bibliometric co-occurrence analysis of author keywords was conducted using VOSviewer (version 1.6.19) to systematically map the thematic structure and interconnections within the pyrogenic carbon and engineered biochar literature. Bibliographic data for all records retrieved from the Scopus database were exported in CSV format and imported into VOSviewer for processing.
Co-occurrence mapping was performed using the full counting method with overlay visualization to reveal both the relational strength between keywords and the temporal evolution of research themes. A minimum co-occurrence threshold of five was applied to retain only the most analytically significant keywords, resulting in the selection of 93 keywords from the complete author keyword set of the retrieved records. These 93 keywords were grouped into thirty-six thematic clusters based on the frequency and strength of their co-occurrence relationships and visualized in Fig.2. The keyword network revealed that "biochar," "pyrogenic carbon," and "carbon sequestration" function as the central connecting nodes of the research landscape. High density peripheral clusters centered on "engineered biochar," "heavy metals," "organic pollutants," and "soil microbial diversity" reflect the dominant applied science orientation of the field.

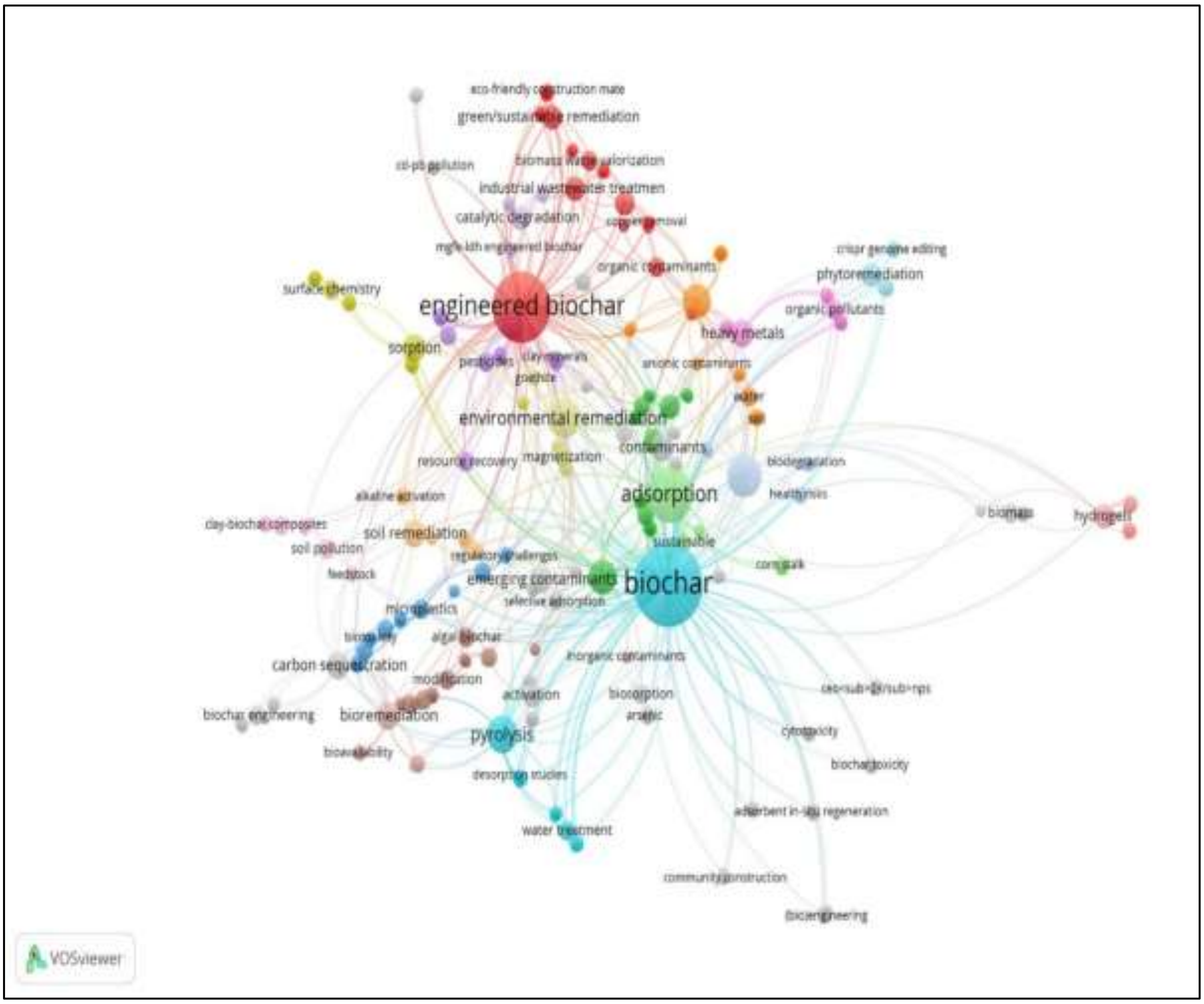

Fig.2. Network visualization and mapping of the co-occurrence of pertinent keywords related to research on advance in engineered biochar

3. Production Pathways of Pyrogenic Carbon
The physicochemical properties of biochar are strongly influenced by the thermochemical conversion process used during its production. Several biomass conversion technologies have been developed to produce biochar and other carbon rich products. These processes differ in terms of temperature, heating rate, residence time, and oxygen availability, which ultimately determine the yield and characteristics of the resulting biochar are shown in Table 1.

4. Molecular Structure and Stability of Pyrogenic Carbon
The remarkable persistence of pyrogenic carbon in soils is primarily attributed to its unique molecular structure. Biochar consists mainly of condensed aromatic carbon structures that are formed during the thermal decomposition of biomass. These structures resemble graphitic carbon networks and contribute to the high chemical stability of biochar.

Table 1. Comparison of major thermochemical conversion technologies used for pyrogenic carbon production

Production Method	Temperature (°C)	Process Conditions	Main Product	Biochar Yield	Key Characteristics	Advantages	Limitations	References
Slow Pyrolysis	300-500	Slow heating rate, long residence time, oxygen-limited environment	Biochar	High	Well-developed pore structure, high carbon stability, moderate surface area	High biochar yield, simple operation, widely used in agriculture	Longer processing time and lower bio-oil production	(53)
Fast Pyrolysis	500-1000	Rapid heating rate, short vapour residence time, oxygen limited environment	Bio-oil	Low	Higher aromaticity and structural stability due to elevated temperatures	Efficient bio-oil production and energy recovery	Lower biochar yield	(54)
Gasification	750-900	Limited oxygen or steam atmosphere	Syngas	Very Low	High mineral content, enhanced surface reactivity	Production of hydrogen rich syngas and energy generation	Limited biochar production	(55)
Hydrothermal Carbonization (HTC)	180-250	High pressure, aqueous environment	Hydrochar	Moderate to High	Carbon rich hydrochar with high energy density	Suitable for wet biomass without pre drying	Product differs from conventional biochar; requires pressurized systems	(56)
Torrefaction	200-300	Mild thermal treatment under oxygen free conditions	Torrefied Biomass	Moderate	Improved fuel properties, reduced moisture content	Low energy requirement and improved biomass handling	Produces torrefied biomass rather than true biochar	(57)
Flash Carbonization	600-1200	Extremely rapid heating and short reaction time	Biochar	Moderate	Rapid biomass conversion and carbonization	Fast biochar production process	Difficult control of biochar properties and product consistency	(58)

4.1 Aromatic Carbon Networks

During the pyrolysis process, aliphatic carbon structures present in biomass are progressively transformed into aromatic carbon structures through dehydration, decarboxylation, and condensation reaction (6) forming stable graphitic like carbon sheets, as shown in Fig.3. This central region of biochar is known as fixed carbon. These reactions lead to the formation of fused benzene rings that combine into polyaromatic clusters, which represent

the fundamental structural units of pyrogenic carbon (7). The degree of aromatic condensation increases with rising pyrolysis temperature, resulting in biochar with higher aromaticity and enhanced structural stability. High temperature biochar exhibits greater resistance to chemical and microbial degradation and long-term persistence in soils due to the presence of condensed aromatic carbon networks linked by strong C-C covalent bonds (8).
In addition to structural stability, the development of aromatic carbon frameworks contributes to increased surface area and porosity, thereby enhancing adsorption capacity. This enables biochar to effectively retain nutrients and contaminants through surface interactions and pore filling mechanisms, supporting its role in soil remediation and nutrient management (9).

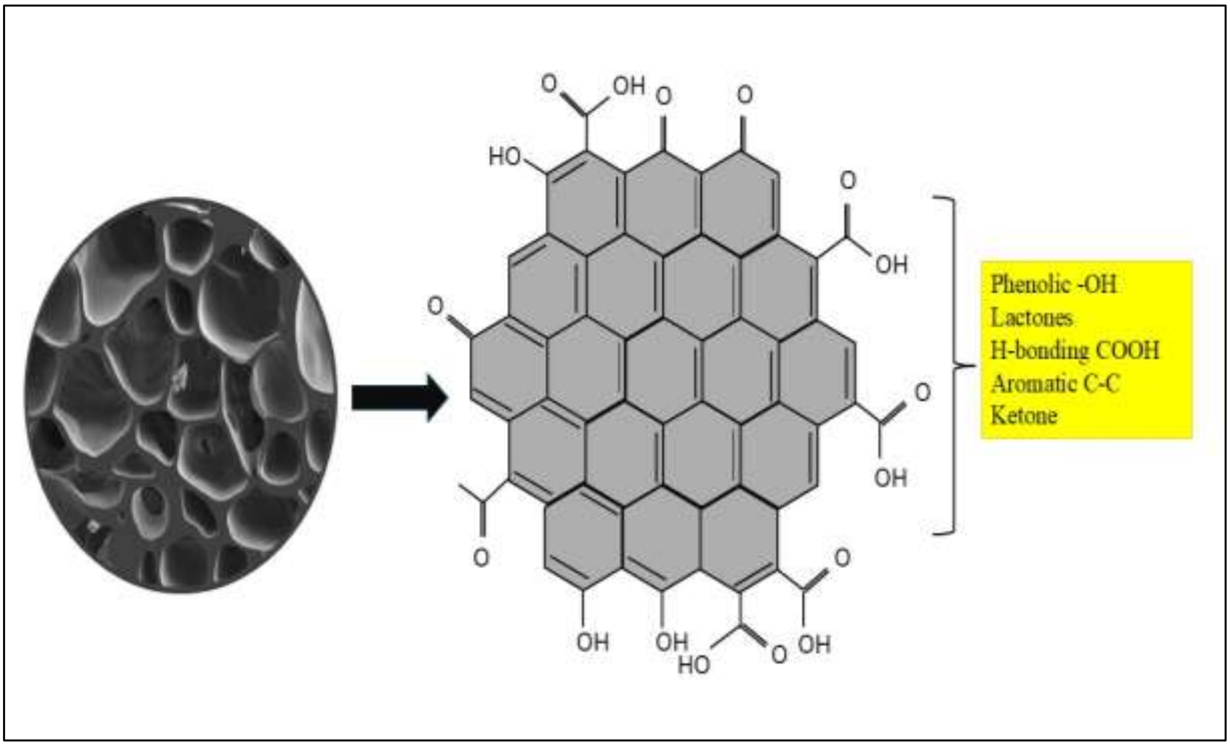

Fig.3.Molecular structure of biochar with functional groups

4.2 Pyrogenic Carbon Mineral Associations

Pyrogenic carbon (PyC) is mineral associations are widely recognized as a critical mechanism governing the stabilization and long-term persistence of biochar in soil systems. PyC interacts with soil minerals through multiple physicochemical processes, including surface complexation, sorption, cation bridging, and physical encapsulation within soil aggregates. Functional groups on PyC surfaces, particularly carboxyl and phenolic moieties, facilitate strong bonding with iron and aluminium oxides, promoting the formation of stable organo-mineral complexes and mineral coatings that protect PyC from microbial degradation. In addition, aggregation and occlusion within soil structure further enhance physical protection and limit decomposition. Evidence from mineral soils indicates that PyC shows strong positive associations with Fe and Al bearing minerals as well as clay and silt fractions, highlighting the dominant role of mineral surfaces in controlling PyC accumulation and persistence, particularly in subsoils where stabilization is enhanced and turnover rates are reduced. While intrinsic properties such as feedstock type and pyrolysis conditions primarily determine PyC chemical recalcitrance, mineral interactions act as a secondary but significant control by modifying mineralization dynamics and extending residence time. These organo-mineral interactions contribute substantially to long-term carbon sequestration and improved soil functionality across diverse environmental conditions (10, 11, 12).

4.3 Microbial Accessibility and Enzymatic Constraints: Beyond Aromatic Recalcitrance

The long-term persistence of pyrogenic carbon in soils is frequently attributed to its highly condensed aromatic structure, which limits microbial utilization and enzymatic degradation. However, recent evidence suggests that biochar stability is more variable than previously assumed and depends strongly on feedstock characteristics, pyrolysis conditions, soil properties, and environmental factors. Traditionally, highly aromatic biochar produced at elevated pyrolysis temperatures (>600°C) have been considered highly resistant to microbial decomposition because they contain condensed polyaromatic structures that require specialized oxidative enzymes such as laccases and peroxidases for degradation. Consequently, many laboratory incubation studies have reported low mineralization rates and predicted residence times ranging from centuries to millennia. However, these estimates may substantially overestimate biochar persistence under field conditions. Meta analysis evidence demonstrates considerable variability in biochar induced carbon cycling responses. Bekchanova et al, analysing 75 studies and 250 observations, reported that biochar increased soil carbon sequestration by 61%, whereas its effects on total microbial respiration and CO_2 flux were statistically inconsistent across studies. Importantly, the authors identified feedstock type, pyrolysis temperature, application rate, and experimental design as major drivers of variability (13). Lower temperature biochar generally stimulated microbial respiration more strongly than highly carbonized biochar, indicating that aromaticity alone does not fully determine microbial accessibility.

Conflicting evidence is also evident when comparing laboratory and field studies. While laboratory incubations commonly report biochar decomposition rates below 3% $year^{-1}$, a recent 15 month field investigation by observed pyrogenic carbon losses ranging from 17.5% to 93.3% $year^{-1}$, with even high temperature (650°C) biochar losing 14.0-51.5% $year^{-1}$(14). These losses were substantially greater than those reported in controlled incubations using the same biochar. Feedstock type further contributes to uncertainty in biochar mineralization dynamics. Woody biochar generally exhibits greater aromatic condensation and lower mineralization rates than manure or grass derived biochar, which often contain larger proportions of labile carbon fractions capable of stimulating microbial activity. Moreover, biochar induced priming effects remain controversial. Some studies report positive priming, whereby biochar stimulates decomposition of native soil organic carbon through enhanced microbial activity, whereas others observe negative priming resulting from physical protection of organic matter and adsorption of extracellular enzymes. Such contrasting observations indicate that biochar soil interactions are highly context dependent.

Biochar aging introduces an additional layer of complexity. Oxidative weathering can increase oxygen containing functional groups on biochar surfaces, enhancing microbial colonization and enzymatic accessibility. Conversely, aging can promote organo-mineral associations and aggregate formation that physically protect biochar from decomposition. Whether aging accelerates or suppresses mineralization therefore remains unresolved and appears to depend on soil mineralogy, climate, and biochar properties. Overall, current evidence suggests that microbial accessibility is controlled not only by aromatic condensation but also by feedstock origin, pyrolysis temperature, environmental conditions, aging processes, and interactions with native soil organic matter. Consequently, predictions of biochar persistence based solely on laboratory incubation studies should be interpreted cautiously. Future research should prioritize long-term field experiments and standardized assessment methods to better quantify biochar mineralization across diverse ecosystems.

5. Engineered and Functionalized Biochar

Although conventional biochar has demonstrated considerable potential as a soil amendment and environmental remediation material, its performance can sometimes be limited by relatively low surface functionality, limited adsorption sites, and variable physicochemical properties. To overcome these limitations, recent research has focused on the development of engineered or modified biochar with enhanced physicochemical characteristics and targeted environmental functions. Engineered biochar is typically produced by modifying the feedstock, altering pyrolysis conditions, or applying post pyrolysis chemical or physical treatments. These modifications can significantly increase surface functional groups, improve adsorption capacity, and enhance catalytic activity. EB has emerged as a highly effective material for the immobilization and removal of metalloids from soil and aqueous environments due to its multifunctional physicochemical properties are discussed in Table 2.

Table 2. Engineered Biochar and their property

Biochar Type	Preparation methods	Materials used	Property	Main Application	References
Mineral based biochar	Co-pyrolysis, Coprecipitation, Mineral immobilization	Montmorillonite, Attapulgite, Struvite, clay minerals	Slow/controlled nutrient release, improved CEC, better soil structure	Soil fertility improvement, Slow release fertilizer, nutrient retention	(59)
Metal doped biochar	Metal salt impregnation and pyrolysis	Fe-oxide biochar, Fe-S biochar	Catalytic redox reactions, magnetic separation, high adsorption	Heavy metal removal, pollutant degradation, wastewater treatment	(60)
Nano zero valent iron (nZVI) biochar	Loading nZVI onto biochar surface	Fe^0 nanoparticles	Strong reduction capacity, electron transfer, contaminant transformation	Cr(VI), Pb, As remediation, groundwater cleanup	(61)

Metal oxide composites	Coating or precipitation of oxides	MgO, MnOx, MoS_2	Surface complexation, catalytic oxidation, high surface reactivity	Organic pollutant adsorption, catalytic degradation	(31)
Microbial (bio-augmented) biochar	Microbe immobilization or inoculation	Bacillus siamensis, Mycobacterium gilvum	Biodegradation & Adsorption synergy, enzymatic breakdown	PAH degradation, nitrogen fixation, metal immobilization, soil bioremediation	(62)
Carbon nanocomposite biochar	Integration with nanocarbons	MWCNTs, graphene	High π-electron density, strong π-π interactions, large surface area	Organic dye removal, antibiotic adsorption, aromatic pollutants	(63)
Graphene based biochar	Graphene coating & functionalization	Reduced graphene oxide (rGO)	Enhanced conductivity, high adsorption sites	Organic contaminant removal, electrochemical remediation	(64)
LDH biochar composites	Layered double hydroxide coating	Mg-Fe, Zn-Al, Ca-Al, Ni-Fe, Mg-Al LDH	Anion exchange, coprecipitation, hydroxyl functional groups	Phosphate & nitrate removal, anionic pollutant adsorption, soil amendment	(65, 66)
Catalytic biochar	Transition metal doping	Fe, Mn, Co, Ni	Fenton like reactions, oxidation catalysis	Advanced oxidation processes, wastewater treatment	(67)
Functionalized biochar (surface modified)	Acid/base/chemical treatment	-COOH, -OH, $-NH_2$ functional groups	Increased surface charge, better adsorption affinity	Heavy metals, dyes, nutrient capture	(68)

As illustrated in the Fig.4, the remediation performance of engineered biochar is governed by a combination of adsorption, surface complexation, ion exchange, electrostatic interactions, redox reactions, and precipitation mechanisms, which operate simultaneously and synergistically.

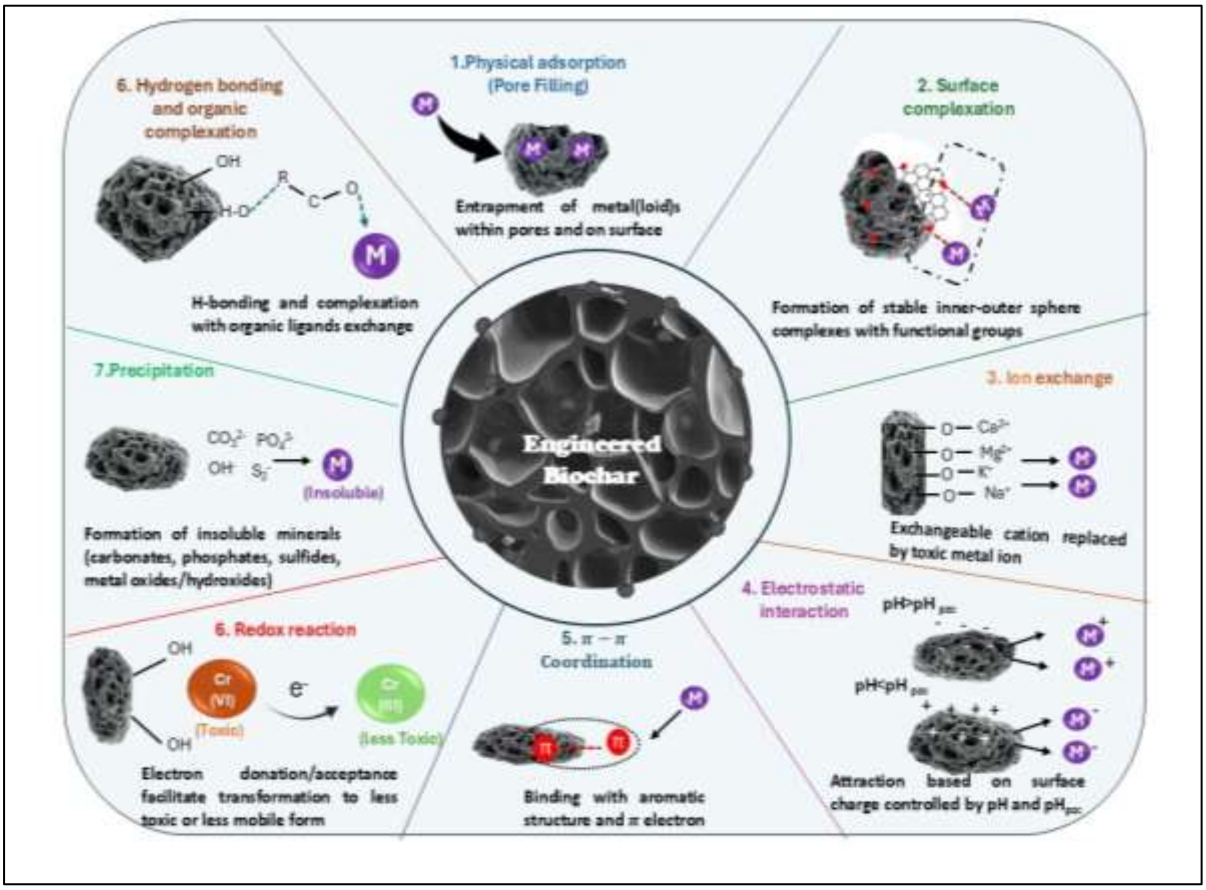

Fig.4. Mechanisms involved in Metal(loid)s immobilization and removal by Engineered Biochar

The highly porous structure and large specific surface area of biochar facilitate the physical entrapment of metal ions through pore filling, providing an initial pathway for contaminant retention. In addition, biochar surfaces are enriched with oxygen containing functional groups such as carboxyl (-COOH) and hydroxyl (-OH), which play a critical role in surface complexation by forming stable coordination bonds with metal ions, thereby reducing their mobility and bioavailability(15). Ion exchange is another important mechanism, particularly in mineral modified biochar, where exchangeable cations such as Ca^{2+}, Mg^{2+}, Na^{+}, and K^{+} are replaced by toxic metal ions from the surrounding environment. Electrostatic attraction further influences metal adsorption and is strongly dependent on the solution pH relative to the point of zero charge (pHpzc) of the biochar surface; negatively charged surfaces at pH values above pHpzc enhance the adsorption of cationic metals, whereas positively charged surfaces favour anion retention. Moreover, π-π interactions and coordination with aromatic structures contribute to the binding of certain metal species, particularly in biochar with a high degree of aromaticity. Moreover, π-π interactions and coordination with aromatic structures contribute to the binding of certain metal species, particularly in biochar with a high degree of aromaticity (16).

Redox reactions also play a crucial role in determining the fate of metal(loid)s, as biochar can act as either an electron donor or acceptor, facilitating the transformation of metals into less toxic or less mobile forms (e.g., reduction of Cr^{6+} to Cr^{3+})(17). Additionally, mineral components inherently present in biochar or introduced during engineering (e.g., carbonates, phosphates, and metal oxides) promote the precipitation of metals as insoluble compounds, further enhancing stabilization. Hydrogen bonding and complexation with organic ligands provide supplementary mechanisms that strengthen metal retention (18). Collectively, these interacting processes make engineered biochar a versatile and sustainable material for environmental remediation, capable of long-term stabilization of contaminants through both physical and chemical pathways (19).'

6. Chemical Modification Mechanisms of Biochar

The untreated form of biochar, which is mainly based on stable aromatic carbon structures, can have limited surface functionality. In order to improve the physicochemical properties, biochar can be chemically modified with different reagents, including alkaline solutions (e.g. NaOH), oxidizing agents, and iron salts, e.g., $FeCl_3.6H_2O$ and $Fe(NO_3)_3.9H_2O$. These types of chemical treatments facilitate oxidation of carbon structures and result in the addition of oxygen based functional groups on the biochar surface hydroxyl (-OH), carboxyl (-COOH), and

carbonyl (-C=O). Introduction of these functional groups considerably enhances the surface charge density, number of active sites and total adsorption capacity of biochar, hence, enhancing its interaction with nutrients in soil. Electrostatic attraction is one of the main mechanisms by which modified biochar can be used to improve nutrient retention. The biochar surface contains negatively charged functional groups that attract, and retain positively charged nutrient such as ammonium (NH_4^+) and potassium (K^+) ions. This electrostatic interaction minimizes the leaching of nutrients and enhances the availability of nutrients within the soil systems. Besides its retention of cations, biochar treated with iron minerals has a high affinity to anions. Ligand exchange and surface complexation of iron functionalized biochar can be used to adsorb negatively charged ions like phosphate (PO_4^-) and nitrate (NO_3^-). This bifunctionality allows biochar to serve as a universal adsorbent of both cationic and anionic nutrients (20).
Moreover, biochar can stabilize nutrients by using chemical precipitation reactions. Nutrients can form insoluble mineral precipitates on the biochar surface, such as struvite ($NH_4MgPO_4.6H_2O$), Strengite ($FePO_4.2H_2O$), and taranakite. These precipitations forms act as slow nutrient storage and help in the increased efficiency of nutrient use and reducing losses due to leaching or run offs, as shown in Fig.5.

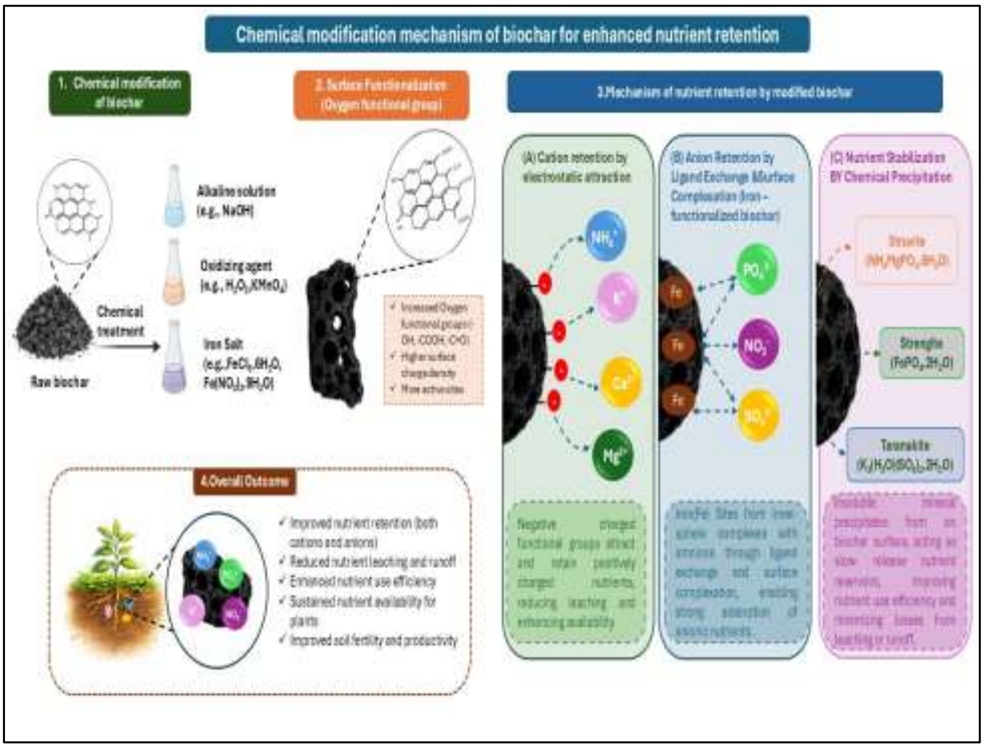

Fig.5. Chemical Modification in Enhancing Cation and Anion Retention on Biochar

6.1 Engineered Biochar in Nutrient Retention and Soil Fertility

One of the most important benefits of biochar application in agricultural soils is its ability to improve nutrient retention and enhance soil fertility. Many soils, particularly tropical and sandy soils, suffer from low nutrient retention capacity and high nutrient leaching losses. Biochar amendments can address these challenges by providing additional adsorption sites and improving soil physicochemical properties. Biochar has emerged as a promising soil amendment for improving nutrient retention and enhancing soil fertility, particularly in light textured soils prone to nutrient leaching, as shown in Table 3. However, pristine biochar often exhibits limited cation exchange capacity (CEC) and anion exchange capacity (AEC), restricting its efficiency in retaining both positively and negatively charged nutrient ions.

Recent studies, including that have demonstrated that chemical modification of biochar can significantly enhance its nutrient retention capabilities. By incorporating oxidizing agents (e.g., O_3, H_2SO_4-HNO_3), alkali treatments (NaOH), and iron based compounds ($FeCl_3$, $Fe(NO_3)_3$), engineered biochar with simultaneously improved CEC and AEC can be produced. These modifications introduce oxygen containing functional groups (e.g., carboxyl and hydroxyl groups) that increase cation adsorption, while iron coatings generate positively charged surfaces (e.g., FeOOH) that facilitate anion retention through electrostatic attraction and ligand exchange mechanisms.

Table 3. Effects of Modified Biochar Derived from Different Feedstocks on Soil Fertility

Biochar feedstock	Soil type	Pyrolysis Temp(°C)	Application rate	Modified biochar	Effect of soil fertility	References
Chemically Modified biochar	Various soils	400-700	Variable	Acid, alkali, metal modified biochar	Increase Nutrient retention, CEC, microbial activity, improved soil fertility, and reduce leaching	(69)
Mineral modified biochar	Agricultural soils	500-700	10-20 t ha^{-1}	Mineral loaded biochar (e.g., Fe, clay)	Increase phosphorus retention, cation exchange capacity, improved long-term fertility	
Rice straw biochar	Pot soil (loamy)	600	2-6% (w/w)	Residue derived biochar	4% application lead to increase plant height (153 cm), seed yield (12.6 g), WHC, reduce bulk density	(70)
Crop residue biochar	Arid agricultural soil	300, 500, 700	10-30 t ha^{-1}	Pristine (temp optimized)	Optimal at 500°C + 20 t ha^{-1} lead to increase potato yield by 27.15%, water holding capacity, aggregate stability	(71)
Crop straw biochar	Saline soil	300, 500, 700	10-20 t ha^{-1}	Temperature modified biochar	700°C + 10 t ha^{-1} lead to soil moisture by 5.6-25%, reduce salinity by 2.9-16.9%, improve maize yield	(72)
Conocarpus biochar	Sandy soil	300	30-60 t ha^{-1}	Low temp biochar	Organic matter increased from 1.2% to 4.43%, water retention, reduce hydraulic conductivity	(73)
Biochar (general)	Acidic soil	400	_	Temperature modified	Soil pH increased from 5.0 to 6.17, improving nutrient availability	(74)
Biochar (general feedstock)	Irrigated soil	_	15-25 t ha^{-1}	Optimized biochar dose	Improves nutrient retention and water use efficiency	(75)

Consequently, such engineered biochar can significantly reduce the leaching of essential nutrients, including ammonium (NH_4^+), nitrate (NO_3^-), phosphate (PO_4^{3-}), and potassium (K^+), while improving nutrient use efficiency (20). Notably, dual modified biochar has been shown to increase nutrient retention by up to 30% for nitrogen forms and substantially improve phosphorus and potassium retention compared to unmodified biochar.

Engineered rice straw biochar increased CEC by up to 66% and AEC by 118%, leading to substantial improvements in nutrient retention, with reductions in leaching of NH_4^+ (33.7%), NO_3^- (27.8%), PO_4^{3-} (15.0%), and K^+ (5.74%) compared to unmodified biochar. These enhancements are attributed to the introduction of oxygen containing functional groups and iron based mineral coatings, which facilitate electrostatic attraction, ligand exchange, and surface complexation mechanisms. Site specific responses indicate that CEC increased by up to 16% in sandy loam soils, while soil pH increased by approximately 0.2-0.3 units, demonstrating biochar's liming effect. Additionally, biochar application reduced electrical conductivity by up to 5% in certain conditions, indicating its potential to mitigate salt accumulation (21).

EB is increasingly recognized as an advanced soil amendment that enhances nutrient retention and soil fertility through improved physicochemical and biological properties. Various types of modified biochar, including physically activated (steam or microwave treated), chemically modified (acid/alkali treated or metal impregnated), biologically engineered (microbe inoculated), and mechanochemically activated (ball milled) biochar, are widely used to improve soil fertility. These modifications enhance surface area, porosity, and functional groups, thereby increasing the adsorption and retention of essential nutrients such as ammonium (NH_4^+), nitrate (NO_3^-), potassium (K^+), and phosphorus (P), while reducing nutrient leaching losses. EB also improves soil structure by increasing porosity, reducing bulk density, and enhancing water holding capacity, which supports root growth and nutrient uptake. Its role in stabilizing soil aggregates further protects nutrients within the soil matrix. Moreover, modified biochar influences nutrient cycling by enhancing microbial activity and enzymatic processes involved in nitrogen transformation, thereby improving nitrogen use efficiency (22). Among various modifications, chemically modified and nutrient rich feedstock biochar (e.g., sewage sludge, manure derived, or alkali treated biochar) are considered the most effective for improving soil fertility due to their high nutrient content, enhanced CEC, and strong adsorption capacity.

Quantitative evidence shows that biochar amendment can significantly improve soil fertility parameters. For instance, application of sewage sludge biochar (100 g Kg^{-1}) in acidic soil increased soil pH by 34.1%, total carbon by 818.2%, and total nitrogen by 550%, demonstrating its strong fertilizing potential. Similarly, biochar application increased available phosphorus by 2.65 fold and potassium by 2.60 fold, highlighting its effectiveness in nutrient enrichment. In another case, biochar enhanced soil organic carbon by 20% and improved water stable aggregates and water holding capacity by up to 39-166%, which are critical for nutrient retention and soil structure improvement (23).

6.2 Biochar Based Slow Release Fertilizer Technologies

Biochar based controlled release fertilizers (BCRFs) improve nutrient use efficiency by leveraging biochar's high surface area, porosity, and functional groups for nutrient adsorption and gradual release. Production methods include impregnation, coating, granulation, co-pyrolysis, hydrothermal synthesis, and in-situ pyrolysis, each offering different levels of control over nutrient release rates.

Nutrient release is primarily governed by dissolution and diffusion, influenced by pore structure and adsorption capacity. Coating with polymers, sulphur, or bentonite further regulates release, while co-pyrolysis integrates nutrients directly into the biochar matrix for more stable retention. BCRFs have demonstrated significant agronomic benefits biochar-based nitrogen fertilizers increased nitrogen use efficiency by 58.8% and crop yield by 16.6% compared to conventional urea, while biochar-based phosphorus fertilizers increased bioavailable soil phosphorus by approximately 72%. Beyond crop nutrition, BCRFs improve soil organic carbon, water retention, and microbial activity, and reduce nutrient leaching, greenhouse gas emissions, and eutrophication risk. These properties make them especially valuable in sandy or tropical soils prone to nutrient loss. However, widespread adoption requires addressing economic feasibility, scalability, feedstock safety, and regulatory frameworks (24).

According to Mustaffa et al, Experimental studies have demonstrated that BSRNF systems can significantly improve soil nutrient balance compared to conventional fertilizers. In many cases, soils treated with biochar embedded fertilizers exhibits higher levels of soil organic carbon, available nitrogen, phosphorus, and potassium at harvest. The improved performance of these fertilizers can be attributed to several mechanisms. First, biochar reduces nitrogen leaching by adsorbing ammonium ions within its pore structure. Second, biochar enhances microbial immobilization of nitrogen, temporarily storing nutrients within microbial biomass. Third, the gradual release of nutrients from biochar matrices ensures that nutrients remain available for plant uptake over longer periods (25).

7. Engineered Biochar in Contaminant Remediation

In addition to its role in improving soil fertility, biochar has also emerged as an effective material for the remediation of contaminated soils and water systems. Its high surface area, porous structure, and diverse functional groups enable biochar to immobilize or degrade a wide range of contaminants.

7.1 Heavy Metal Immobilization

Biochar can reduce the mobility and bioavailability of heavy metals such as cadmium, lead, zinc, and nickel in contaminated soils. Several mechanisms contribute to heavy metal immobilization. First, heavy metal ions can be adsorbed onto the biochar surface through electrostatic attraction and ion exchange processes. Second, metal ions may form stable complexes with functional groups present on the biochar surface. Third, metals can precipitate as insoluble mineral compounds in the presence of minerals contained in biochar. These processes can significantly reduce metal uptake by plants and decrease environmental toxicity.

In a recent study, micro nano engineered nitrogenous bone biochar was developed via ball milling of pyrolyzed cow bone. This engineering process resulted in a substantial reduction in particle size to the micro nano scale and a marked increase in specific surface area, porosity, and exposure of active functional groups. Compared to pristine biochar, the ball milled biochar exhibited significantly enhanced adsorption performance for heavy metals such as Cd (II), Cu (II), and Pb (II). Notably, the adsorption capacities of the engineered biochar (MBC-600) reached 165.77 mg g^{-1} for Cd (II), 287.58 mg g^{-1} for Cu (II), and 558.88 mg g^{-1} for Pb (II), representing improvements of up to approximately 94% relative to unmodified biochar (26). Additionally, the presence of hydroxyapatite ($Ca_5(PO_4)_3OH$) in bone derived biochar provides abundant phosphate and hydroxyl groups, which play a crucial role in metal binding. Functional groups such as -OH, -COOH, and nitrogen containing moieties further contribute to the adsorption process by acting as active binding sites for metal ions (27). BC Nanoparticles, particularly those modified with nano silicon (nSi) and nano iron (nFe), show enhanced efficiency in removing cadmium (Cd) from contaminated soils. The composite reduced bioavailable Cd by 21% and decreased shoot Cd accumulation by 78%, indicating effective immobilization.

Engineered biochar (EB), particularly metal functionalized biochar, has shown significantly enhanced performance in contaminant removal compared to pristine biochar. For instance, nano zerovalent zinc functionalized biochar (nZn^0 BC) demonstrated high removal efficiencies of 93% for selenite (Se (IV)) and 94% for selenate (Se (VI)) at an adsorbent dose of 2 g L^{-1} and contact time of 24 h. The adsorption followed pseudo second order kinetics described by the Langmuir isotherm (R^2 value 0.98-0.99), indicating chemisorption and monolayer adsorption behaviour. The maximum adsorption capacities were reported as 23.83 mg g^{-1} for selenite and 27.16 mg g^{-1} for selenate, which are significantly higher than many conventional adsorbents. The material maintained high removal efficiency (>91%) across a wide pH range of 410, demonstrating strong environmental adaptability (28).

EB particularly nano zero valent iron (nZVI) and iron oxide (FeOx) modified biochar, has shown significantly enhanced efficiency for the removal of toxic elements (TEs) such as Cr, As, Pb, Cd, and Hg from aqueous environments. nZVI modified biochar achieved 98.2% removal of Cr (VI), compared to 16.2% by pristine biochar and 47.9% by nZVI alone, demonstrating strong synergistic effects. The maximum adsorption capacity for Cr (VI) reached 56.79 mg g^{-1}, with equilibrium achieved within 30 min. Similarly, sludge derived nZVI biochar showed a capacity of 28.89 mg g^{-1} for Cr (III) through precipitation mechanisms.

For arsenic removal, Fe modified biochar exhibited adsorption capacities up to 124.5 mg g^{-1} for As(V), with equilibrium reached within 1 h, and even achieved 100% removal under flow conditions (2.1 mg L^{-1}). Another study reported 28.49 mg g^{-1} adsorption capacity via Fe-As surface complexation mechanisms. Engineered biochar modification significantly enhances surface properties. For instance, surface area increased from 84.3 to 509.2 m^2 g^{-1} after nZVI loading, leading to improved adsorption performance. Additionally, hydrothermal modification increased Cr (VI) adsorption capacity to 83.02 mg g^{-1}, compared to 70.79 mg g^{-1} in conventional biochar (29). The removal mechanisms involve multiple pathways, including adsorption, reduction, coprecipitation, and surface complexation. For example, Cr (VI) is reduced to the less toxic Cr (III), followed by precipitation as $FeCr_2O_4$, while arsenic is immobilized through Fe-O-As complex formation.

Nano BC has demonstrated significantly enhanced efficiency for the removal of potentially toxic elements (PTEs) such as Cd (II), Zn (II), and Pb (II) from aqueous systems. Compared to bulk biochar, nanoscale modification increases surface area, pore volume, functional groups, and negative surface charge, resulting in improved adsorption performance. The adsorption capacity of engineered biochar increased by 2.1-53.9% for Cd(II), 14.3-48.3% for Zn(II), and up to 332% for Pb(II), with maximum Pb(II) adsorption ranging from 276.4 to 431.9 mg g^{-1} (30) .The removal process involves multiple mechanisms, including surface complexation, electrostatic attraction, and intraparticle diffusion, with adsorption occurring in distinct stages from rapid surface binding to slower pore diffusion. Performance is strongly influenced by feedstock type and pyrolysis conditions, with optimal adsorption observed at 550-650°C.

EB, particularly nano metal oxide biochar composites (NMOBCs), has emerged as an advanced material for efficient removal of environmental contaminants. NMOBCs effectively remove a wide range of contaminants, including heavy metals (Pb^{2+}, Cd^{2+}, Hg^{2+}), inorganic anions (phosphate, nitrate), and organic pollutants (dyes, pesticides, pharmaceuticals) through combined adsorption and photocatalytic degradation mechanisms. For example, adsorption capacities vary significantly depending on the metal oxide used, with nano MnO_2 biochar achieving up to 305.25 mg g^{-1} for Pb (II), while nano NiO biochar shows lower capacity (28 mg g^{-1}), indicating strong dependence on composite composition (31).

7.2 Organic Pollutant Removal

Biochar has also demonstrated strong potential for the adsorption of organic pollutants including pesticides, phenols, antibiotics, dyes, and hydrocarbons. The aromatic carbon structure of biochar enables strong π-π interactions with aromatic organic molecules. In addition to physical adsorption, biochar can also support microbial communities capable of degrading organic contaminants. The porous structure of biochar provides protective microhabitats for microorganisms, which enhances microbial biodegradation processes.

For instance, modification with photocatalytic materials significantly improves degradation efficiency. TiO_2 biochar enhanced dye (Reactive Blue 69) degradation from 63.8% to 98.1%, maintaining 92.1% efficiency after five cycles, indicating strong stability. Similarly, functionalized composites such as biochar-g-C_3N_4 and graphene based biochar improve removal of dyes (e.g., methylene blue, methyl orange) and organic compounds through combined adsorption and photocatalysis. Biochar also acts as an electron mediator, enhancing charge separation and increasing degradation efficiency under light irradiation (32).

EB has emerged as an efficient material for the removal of organic pollutants such as polycyclic aromatic hydrocarbons (PAHs) and pesticides from water systems. Its high surface area (up to 1500 $m^2\ g^{-1}$), porosity, and tunable surface functional groups enable adsorption efficiencies exceeding 90% under optimal conditions. Modification strategies, including chemical activation, metal doping, and nanocomposite formation, significantly enhance removal performance. Engineered biochar integrated with advanced oxidation or photocatalytic systems can achieve up to 98-99% removal efficiency, promoting degradation of persistent organic pollutants into less toxic forms. For pesticides, engineered systems demonstrate high efficiency, with reported values such as 96.25% chlorpyrifos removal within 24 h and 99.7% paraquat removal, along with adsorption capacities up to 738 mg g^{-1} (33).

Biochar significantly enhances sorption of compounds like phenanthrene and sulfamethazine, with reported sorption strength up to 10-1000 times higher than soil organic matter, even at low biochar application rates. EB composites further improve removal efficiency by incorporating nanomaterials and catalysts. For instance, multilayer graphene biochar achieved 99.6% removal of tetracycline within < 30 min, with an adsorption capacity of 388.3 mg g^{-1}, while MoS_2 biochar showed 249.45 mg g^{-1} capacity for antibiotic removal. Additionally, 3D porous biochar aerogels exhibited extremely high capacities (up to 786.1 mg g^{-1}) for antibiotics due to enhanced pore structure and surface interactions. Beyond adsorption, EB enables catalytic and photocatalytic degradation of organic pollutants. For example, nZVI biochar composites achieved 99.4% degradation of trichloroethylene within 5 min, while biochar supported catalysts enable 94-100% degradation of compounds such as aniline and dyes under catalytic or light assisted conditions (34). These processes involve reactive species such as OH, SO_4^-, and O_2^- radicals, which break down pollutants into less toxic compounds.

Modification of biochar with metal oxides and semiconductors (e.g., ZnO, Fe_3O_4, g-C_3N_4) significantly enhances its catalytic activity by improving surface area, charge transfer, and active site availability. Experimental studies report high removal efficiencies, including 99% phenol degradation within 90 min, 96% BPA removal in 60 min, and 97% dye degradation within 2 h, while antibiotic removal efficiency reaches 81%. These high efficiencies are attributed to improved light absorption and reduced bandgap energy (e.g., from 2.26 to 1.70 eV), enabling effective photocatalytic activity under visible light (35). Challenges remain, including unclear degradation pathways, difficulty in detecting intermediate products, and potential toxicity of by-products. As highlighted in the conclusion, photocatalytic degradation requires advanced analytical and computational approaches for mechanism clarification.

7.3 Arsenic Stabilization Using Modified Biochar

Although conventional biochar can effectively immobilize many heavy metals, its ability to adsorb arsenic is often limited. In some cases, biochar may even increase arsenic mobility due to pH changes in soil. To address this limitation, researchers have developed modified biochar incorporating metal oxides such as zirconium oxide. Nano zirconia modified biochar has demonstrated significantly improved arsenic adsorption capacity.

These materials provide additional adsorption sites and form strong chemical bonds with arsenic species through surface complexation reactions involving hydroxyl and carboxyl functional groups. Laboratory studies have shown that such modified biochar can reduce arsenic leaching by more than 99%, demonstrating their strong potential for soil remediation applications (36).

8. Effects of Biochar on Soil Physical, Chemical, and Biological Properties

Biochar application can influence a wide range of soil properties, including physical structure, chemical fertility, and biological activity. These improvements contribute to enhanced soil health and agricultural productivity.

8.1 Soil Physical Properties

One of the most significant physical effects of biochar addition is the reduction of soil bulk density. Due to its porous structure and relatively low density, biochar incorporation can decrease soil compaction and improve soil structure. Studies have reported reductions in bulk density of up to 29% following biochar application. At the same time, soil porosity can increase significantly, often by more than 50% (37). Increased porosity improves soil aeration, water infiltration, and root penetration. Biochar also enhances the water holding capacity of soils. The highly porous structure of biochar allows it to store water within its pore network, making moisture available to plants during periods of drought stress.

Biochar application significantly improves soil physical properties due to its low density and highly porous structure. It reduces soil bulk density by 3-31% and decreases particle density, leading to improved soil aeration, root penetration, and workability. Concurrently, biochar increases soil porosity by 14-64%, enhancing gas exchange and microbial activity, particularly in coarse textured soils. It also improves soil structural stability, with wet aggregate stability increasing by 3-226%, thereby reducing erosion and enhancing resilience. It enhances soil water retention, increasing available water content by 4-130%, which is especially beneficial in sandy soils.

8.2 Soil Chemical Properties

Biochar can significantly influence soil chemical characteristics. Many biochar contains alkaline minerals such as calcium, potassium, and magnesium, which can increase soil pH when applied to acidic soils. Its application significantly enhances soil chemical properties by improving nutrient availability, carbon content, and cation exchange capacity (CEC). Biochar is inherently rich in essential nutrients such as Ca, Mg, K, and P, with concentrations reported as 3361 mg kg^{-1} Ca, 2133 mg kg^{-1} Mg, 8615 mg kg^{-1} K, and 1859 mg kg^{-1} P, which are substantially higher than those in most soils. Its addition increases soil organic carbon (SOC), with carbon content rising by up to 4.2-6.6 kg kg^{-1} depending on soil type and particle size. Furthermore, biochar slightly increases total nitrogen content, although changes are often minimal in short term studies. It influences the C:N ratio, which may increase significantly, particularly in sandy soils, improving nutrient cycling and microbial activity. Another key effect is the enhancement of soil pH, especially in acidic soils, leading to reduced aluminium toxicity and improved nutrient availability. Additionally, biochar can improve CEC due to its high surface area (up to 371 m^2 g^{-1}) and surface functional groups, thereby enhancing nutrient retention and reducing leaching losses (38).

8.3 Soil Microbial Diversity

Biochar can also influence soil microbial communities. The porous structure of biochar provides microhabitats that protect microorganisms from environmental stresses while offering surfaces for microbial colonization. It influences soil microbial properties, particularly microbial biomass, diversity, and community composition. Meta analysis evidence indicates that biochar generally increases total microbial biomass, including both bacterial and fungal populations, primarily due to the availability of labile carbon and nutrients that stimulate microbial growth. The porous structure of biochar provides protective microhabitats, enhancing microbial colonization and reducing predation pressure. Additionally, biochar improves soil physicochemical conditions such as pH, cation exchange capacity, and aeration, indirectly promoting microbial activity and proliferation. However, the effects on microbial diversity are variable and highly dependent on soil type and biochar properties. While microbial diversity often increases in acidic, sandy, and low organic carbon soils, some studies report reduced diversity due to selective stimulation of specific microbial groups. For instance, dominant taxa such as Actinobacteria and Firmicutes may proliferate, leading to shifts in community composition. Biochar produced at lower pyrolysis temperatures and derived from nutrient rich feedstocks (e.g., manure) shows the greatest positive impact on microbial biomass and diversity (39).

BC amended soils showed significant increases in SOC (18.5%), TN (19.0%), and AP (73.7%) in deeper soil layers, which directly support microbial growth and metabolism. Biochar also alters microbial community composition by promoting dominant bacterial groups such as Actinobacteria, Proteobacteria, Chloroflexi, and Acidobacteria, which together account for more than 79% of the total microbial abundance. Additionally, specific bacterial families such as Gaiellales, Sphingomonadaceae, and Nocardioidaceae become more abundant under biochar treatments, indicating shifts in functional microbial communities involved in nutrient cycling. Moreover, biochar indirectly regulates microbial diversity through its influence on soil nutrients and pH, which were identified as key drivers of microbial community structure (40). However, its effects vary with soil depth and management practices for example, microbial richness showed limited response in some layers despite improved soil conditions.

9. Biochar Organic Amendment Interactions and Soil Carbon Stability

Recent research has increasingly focused on the synergistic interactions between biochar and organic amendments such as manure, compost, and crop residues. While biochar is primarily composed of stable, recalcitrant carbon, organic amendments contain more labile carbon fractions that stimulate microbial activity and nutrient cycling (41). The combination of these materials can therefore produce complementary effects that enhance soil carbon stabilization and ecosystem functioning.

Biochar provides a stable carbon framework that persists in soil for long periods, whereas manure supplies readily decomposable organic substrates that support microbial metabolism. When applied together, these amendments improve both short term nutrient availability and long-term carbon storage (42, 43). Combined biochar manure applications significantly increase total organic carbon (TOC) compared to individual amendments. The addition of manure enhances microbial activity and promotes the formation of microbial biomass and extracellular polymers, which bind biochar and mineral particles into stable aggregate.

Furthermore, biochar–manure interactions improve soil structure and porosity, leading to enhanced water infiltration and root growth (44). Soil microbial communities also respond positively, with increased abundance of beneficial groups such as Proteobacteria and Chloroflexi due to improved pH and nutrient availability. In addition, enzyme activities such as urease and catalase are often stimulated, reflecting enhanced nutrient cycling, although some hydrolase activities may be inhibited by biochar derived phenolic compounds (45).

10. Planetary Scale Impacts of Pyrogenic Carbon

Beyond its local soil benefits, pyrogenic carbon has important implications for global environmental processes and planetary sustainability. Biochar is increasingly recognized as a potential negative emission technology capable of removing atmospheric CO_2 and storing it in terrestrial ecosystem. Global soil inventories estimate that approximately 200 Pg of pyrogenic carbon are stored in the upper two meters of soils worldwide, highlighting its significance in long-term carbon cycling (46, 47). Recent largescale assessments highlight the significant contribution of pyrogenic carbon (PyC) to global carbon storage and climate regulation. (48) demonstrated that PyC contributes substantially to soil organic carbon pools across tropical savannas, accounting for an average of 14.08% of soil organic carbon and reaching values as high as 40% in some locations. These suggest that pyrogenic carbon functions as a significant long-term carbon sink and emphasize the importance of considering ecosystem specific preservation mechanisms when evaluating the contribution of fire derived carbon to global carbon budgets and climate change mitigation strategies.

PyC as a long-term carbon sink, substantial uncertainties remain regarding its actual contribution to global carbon sequestration. (49) demonstrated that while wildfire derived PyC contributes to long-term soil carbon accumulation, this benefit is partially offset by carbon losses through mineralization, riverine export, incomplete vegetation recovery, and soil degradation. Their modelling analysis estimated a residual global carbon sink of approximately 89 Tg C yr^{-1}. however, the authors emphasized that this estimate remains highly uncertain because PyC mineralization rates are poorly constrained. Reported mean residence times vary from decades to thousands of years, reflecting significant inconsistencies among laboratory incubations, field observations, and radiocarbon based assessments. Furthermore, the study revealed contrasting ecosystem responses, with grassland savanna systems functioning as potential net carbon sinks, whereas forest ecosystems often exhibited net carbon losses. These findings challenge the generalized assumption that pyrogenic carbon universally enhances carbon sequestration and highlight the importance of considering biome specific dynamics, environmental controls, and multiple carbon loss pathways when evaluating the long-term climate benefits of pyrogenic carbon.

The conversion of agricultural residues into biochar can reduce greenhouse gas emissions by preventing open burning and stabilizing carbon in recalcitrant forms. Large scale biochar deployment could mitigate approximately 66-130 billion tons CO_2 equivalent emissions per century, with each ton of biochar sequestering about 2.0-2.6 tons of CO_2 (50). Additionally, biochar application can reduce N_2O emissions by improving nitrogen retention and may also decrease CH_4 emissions through enhanced soil aeration and microbial oxidation (51). At broader scales, biochar contributes to ecosystem restoration by improving soil fertility, water retention, and resilience in degraded soils. It also supports circular bioeconomy systems by converting agricultural wastes into valuable carbon products, reducing pollution and creating rural economic opportunities. From a planetary boundary perspective, biochar can help regulate climate change, land use systems, nutrient cycling, and atmospheric aerosols, offering a multifunctional approach to global sustainability challenges (52).

11. Research Gaps and Future Research Directions

Despite the growing body of research on engineered biochar, critical knowledge gaps limit its confident application as a soil quality improvement technology. These gaps span all dimensions of soil health biological, chemical, physical, and long-term stability and must be systematically addressed before large scale deployment can be recommended.

11.1 Lab to Field Persistence Gap

The most fundamental gap concerns the substantial discrepancy between laboratory predicted and field observed biochar persistence, as presented in Table 4. While laboratory incubations consistently report mineralization rates below 3% $year^{-1}$, field data document losses of 17.5 to 93.3% $year^{-1}$ (14). This discrepancy, driven by wet dry cycles, microbial adaptation, and physical weathering absent in lab settings, means that anticipated long-term soil quality benefits improved SOC, aggregate stability, and CEC may not materialise at the timescales required for agricultural planning or carbon credit validation. Future research must prioritise multiyear, multisite field trials using ^{13}C labelled engineered biochar to definitively quantify field scale persistence across soil types and climates.

11.2 Pot to Field Nutrient Retention Translation

Although engineered biochar show impressive CEC and AEC gains in pot studies (up to 66% and 118% increases respectively), no field scale validation of nutrient retention and crop yield response to engineered biochar currently exists. Field lysimeter studies measuring leachate nutrient concentrations and actual crop NUE over multiple growing seasons, across contrasting soil textures and climates, are needed.

Table 4. Gap Between Lab Scale and Field Scale Biochar Experiment

Category	Lab condition	Field condition	Key gap
Biochar age	Fresh biochar applied at time of experiment	Biochar aged 2-7 years in soil before measurement	Aging reduces surface reactivity, liming effect, and electron shuttle capacity. Lab results from fresh biochar cannot predict aged biochar behaviour. No standardised aging protocol exists.
Biochar application rate	Higher rates commonly used (up to 5% w/w or >20 t ha^{-1}) to detect effects	Lower agronomic rates (0.5-9.3 Mg ha^{-1} dry weight) reflecting practical constraints	Effect sizes in lab are inflated by high rates. Field studies using lower rates show smaller and often non-significant effects. Rate response

			relationships are poorly characterised across realistic field rates.
Study duration	60-140 days for GHG; hours to weeks for adsorption columns	Field studies span one to multiple growing seasons; Liao et al. measured 7 years post-application	Short term lab effects (labile C mineralisation, initial N_2O flush) are not representative of long-term field dynamics. Biochar effects on GHG and soil physical properties change substantially over years.
Moisture regime	Static moisture levels set at −1, −1/3, −1/10 bar; narrow range (27–35%)	Dynamic wetting drying cycles; field moisture often exceeded 35% after rainfall events	Lab does not replicate natural wetting drying pulses that drive N_2O emission spikes. Biochar effect on moisture sensitivity of N_2O production is untested across realistic moisture ranges.
Soil spatial variability	Single homogenised soil sample from one plot; sieved and repacked	Natural soil variability across four plots per treatment; multiple soil series (Ackmore, Clarinda, Exira, Marshall)	Lab uses a single representative soil; field has inherent spatial heterogeneity that inflates variance and obscures treatment effects. Type II statistical errors likely in both N_2O and soil physical data.
Biological inputs	No live roots; no above-ground biomass; no root exudates; no litter inputs	Active root systems, root exudates, crop residues, and soil fauna present throughout growing season	Root respiration, rhizosphere priming, and litter decomposition all contribute to CO_2 and N_2O fluxes at field scale. These biological drivers are entirely absent from lab incubations.
Upscaling models	Thomas, Yoon-Nelson, Hydrus 1D calibrated to column data under controlled conditions	No validated upscaling framework links lab adsorption parameters to PRB or pump and treat performance in heterogeneous aquifers	Lab derived parameters (k_{th}, q_m, dispersivity) are rarely validate against field scale remediation outcomes. A standardised protocol for translating column results to field design is absent from the literature.
Statistical power and replication	5 replicates per treatment; controlled variance; outliers removed by Q-test	4 field replicates per treatment; high spatial and temporal variance; Nelissen et al required 14 sensors for adequate VWC detection power	Field N_2O and soil physical data have high natural variance, increasing Type II error risk. Many non-significant field results may reflect underpowered designs rather than absence of effect. Power analysis is rarely reported.
Flow and transport dynamics	Column experiments: controlled flow rates (0.1-5 mL/min), uniform packing, laminar flow assumed	Preferential flow paths, macropores, uneven infiltration, seasonal water table fluctuations	Lab column parameters (Thomas model k_{th}, breakthrough times) derived under idealised laminar flow do not account for preferential flow or bypass phenomena present in structured field soils.

11.3 Functional Soil Biology Under Engineered Biochar

All reviewed microbial diversity studies concern pristine biochar. The effects of nano modified, iron functionalized, and LDH biochar variants on functional microbial guilds nitrogen fixers, ammonia oxidisers, phosphorus solubilisers, and mycorrhizal fungi are entirely absent. Given that these guilds directly drive nutrient cycling and disease suppression, their response to reactive engineered biochar surfaces represents a critical knowledge gap. Functional metagenomics combined with enzyme activity profiling under engineered biochar treatments is a priority for soil biological quality research.

11.4 Ecotoxicological Safety of Nano Engineered Biochar

The reactive nanoparticle surfaces (nZVI, nano MnO_2, nano ZnO) that confer high contaminant removal efficiency may equally threaten soil organisms. Standardised ecotoxicity assays (ISO earthworm reproduction, phytotoxicity, nematode assays) for nano EB at agronomic application doses, combined with nanoparticle fate and transport studies in soil matrices, must be completed before any large scale field application of nano modified biochar is recommended.

11.5 Long-term Metal Remobilisation in Remediated Soils

Batch adsorption studies demonstrate high metal removal efficiencies for engineered biochar, but provide no information on metal stability under long-term soil conditions. Changes in soil pH, redox potential, and competing ligand concentrations during ageing may release previously immobilised metals back into the soil solution. Sequential chemical extraction studies at 1, 2, and 5 year intervals in EB remediated contaminated soils are essential to confirm whether engineered biochar provides a permanent or temporary immobilisation of metal contaminants.

11.6 pH Management Risk in Non-Acidic Soils

The alkaline nature of most engineered biochar particularly alkali treated and mineral loaded variants carries a risk of over liming in neutral or alkaline soils, which could induce micronutrient deficiencies and reduce overall soil quality. Systematic pH buffering characterisation of each EB class, combined with dose response trials across soil pH gradients (pH 4.5-8.5), is needed to define safe application windows and prevent unintended soil quality degradation.

11.7 Biochar Based Fertilizer Performance Under Climate Variability

Biochar based slow release fertilizer technologies show strong nutrient use efficiency gains under controlled conditions. However, performance under climate variable field conditions extreme rainfall, drought, and freeze thaw cycling remains untested. As these are precisely the conditions under which conventional fertilizer losses are greatest, and which are increasing in frequency under climate change, research on BCRF resilience across these stress conditions is an major priority for sustainable soil fertility management.

12. CONCLUSION

Pyrogenic carbon, particularly in the form of biochar, represents a highly stable form of carbon with significant potential for improving soil health and mitigating climate change. The unique molecular structure of biochar, characterized by condensed aromatic carbon networks and strong mineral associations, enables it to persist in soils for extended periods while enhancing nutrient retention and soil functionality. Advances in engineered and nanomodified biochar have expanded the applications of biochar beyond conventional soil amendments to include contaminant remediation, nutrient management, and environmental restoration. Biochar application can significantly improve soil physical, chemical, and biological properties by increasing porosity, cation exchange capacity, microbial diversity, and nutrient availability. The integration of biochar with organic amendments and fertilizer technologies further enhances soil carbon stability and agricultural productivity. At a global scale, biochar contributes to carbon sequestration, greenhouse gas mitigation, soil restoration, and circular bioeconomy development.

Despite these promising benefits, further research is needed to address uncertainties related to long-term biochar stability, environmental safety of engineered biochar, and large scale implementation strategies. Continued interdisciplinary research integrating soil science, environmental chemistry, microbiology, and climate science will be essential to fully realize the potential of next generation pyrogenic carbon for sustainable agriculture and planetary resilience.

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Conflict of Interest

The authors declare no competing interests.

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