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REVIEW

Biochar as a Climate-Smart Agricultural Practice: Reducing Greenhouse Gas Emissions and Promoting Sustainable Farming

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ABSTRACT

In recent years, the world has faced rising global temperatures, accumulative pollution, and energy crises, stimulating scientists worldwide to strive for eco-friendly and cost-effective solutions. Biochar has materialized as a favorable tool for environmental remediation, indicating efficacy as an efficient sorbent substance for both inorganic and organic pollutants in environmental field. These unique properties exclude improved surface functionality, porous morphology, large specific surface area (SSA), cation exchange capacity (CEC), robust adsorption capabilities, environmental stability, and embedded micronutrients. Biochar exhibited potential characteristics for environmental oversight, greenhouse gas (GHG) emission reduction, and soil fertility improvement. This review explores the impact of fundamental factors such as retention time, pyrolysis temperature, gas flow rate, and reactor design on biochar yield and properties. Collected data revealed the various applications of biochar, ranging from waste management and construction materials to the adsorptive removal of hydrocarbon lubricants from aqueous media, contaminant immobilization, and carbon sequestration. It has played mostly a significant share in climate change mitigation and an important role in soil amendments. Biochar improves soil improvement by increasing water retention (10%–30%), carbon sequestration, soil surface functionality, and providing high surface area with chemical stability. The assessment also reports the prospects and contests associated with biochar application uses in various agriculture cropping ecosystems. Inclusive, this review highlights the multifaceted characteristics of biochar as an adjustable on top of a sustainable solution addressing greenhouse gas emission, carbon sequestration, and environmental stresses. However, further research is needed to understand its long-term impacts and optimal applications fully.

KEYWORDS

Agro-ecology; biochar; carbon storage; greenhouse gas reduction; sustainable agriculture

1 Introduction

Accelerating ecological pollution, energy predicaments, unfettered advanced proceedings, and climate change triggered by global warming have been the furthest unrelenting global challenges [1]. Amplified greenhouse gas (GHG) emissions subsequently human actions have consequences in an all-embracing intensification in worldwide temperatures gradually day by day, [2] mostly raised under the umbrella of global warming [3]. This distinctiveness has stimulated a series of unswerving activities, such as climate change, exposure to drought events or water stress, plant diseases, and biodiversity loss [4]. In addressing these challenges, learning about innovative applications and adaptive strategies, laterally with resourceful solutions, is essential to mitigate existing and projected climate change influences [5]. At the same time, efficiently utilizing and managing the substantial outputs and raw materials produced from agricultural activities also practices leftovers, which is a paramount concern [1,6].

Prevailing agricultural waste management techniques, including composting, crop residue, and burning, raise various environmental concerns [7]. These methods contribute to the primary emission of GHGs, such as nitrous oxide, carbon dioxide, and methane [8]. Among these, carbon dioxide is the primary GHG legally responsible for driving climate change [9]. In contrast, the agricultural segments are responsible for approximately 13.5% of total anthropogenic greenhouse gas emissions [10]. There is increasing awareness of utilizing organic waste and agricultural inputs from urban and rural areas as a renewable and sustainable resource for agriculture production [11]. Biochar is a reservoir of electron acceptors and donors with a pH buffering range and Cation Exchange Capacity [12]. These qualities elevate biochar reactivity, influenced mainly by source ingredients and manufacturing procedures. Biochar is a well-known carbonaceous substance, commonly synthesized in an oxygen-restricted condition through thermos-chemical processes like gasification [13], slow or fast pyrolysis [14], hydrothermal carbonization (HTC) [15], torrefaction [16] as well as the regulation of the pyrolysis assay and its consequential modification [17], etc. Biochar investigation has taken considerable time recently, and significant beneficial progress has been reported. Biochar has quite a lot of inimitable characteristics together with an improved permeable porous nature, the existence of oxygen-holding outward efficient functional groups, fabulous CEC [18], growth and increased surface area, strong adsorption capabilities, structural stability, upgrading with essential minerals and approximately trace metals [19].

As a result of its physical and chemical potentials, biochar adaptability extends several applications, including soil upgrading, contaminant restriction, carbon storage, and decreasing greenhouse gas emissions [20]. It also helps as an improver trendy an-aerobic assimilation, composting, and microbiological fuel cells [21]. Dai et al. defined biochar as a sustainable adsorbent for removing various pollutants, including organic contaminants such as insect repellents, dyes, antibiotics, and heavy metals like lead, arsenic, and mercury [22]. Li et al. proved that biochar also effectively removes inorganic contaminants, such as orthophosphate and nitrate, from water sources [23].

Ma et al. highlighted that recent studies and assessments suggest biochar has potential applications in energy and environmental division, with multifaceted benefits that still require further investigation in ongoing research [24]. Much research has emphasized the outcome of biochar as a soil amendment proceeding GHG emissions and restraining the practice of contaminated elements intended for soil [25]. Das et al. have provided visualizations of the proficiency of biochar alteration on soil systems and physicochemical and biological properties [26]. Moreover, Ralebitso-Senior et al. observed that the accumulation of biochar stimulated microbial activity, contributing to the enhancement of soil quality and overall soil health [27].

The general management of biochar as both a catalyst and catalyst support in organic pollutant degradation via (AOPs) advanced oxidation processes and utilization in bio-refineries has been comprehensively discovered in research [28,29]. Ambika et al. conducted a comprehensive review on the use of biochars for Cr (VI) elimination from various sources and the underlying mechanisms in soil [30]. Despite these innovations, an inclusive synthesis of biochar and methods, ecological implications, and benefits has not been scientifically accumulated in the existing literature. Therefore, this review objective is to fill this gap by providing an in-depth scientific outline of these characteristics. It covered biochar's production and the influence of thermos-chemical parameters on its properties. It systematically deliberates conservation management strategies like GHG mitigation in soil, alterations in properties of soil, soil-microbe interactions, heavy metals (HMs) activities in soil, and bio-availability interactions with biochar, as well as its economic prospects and future research directions. These are three questions that aim to comprehensively address the objectives and extensive consequences of this review study:

1. How does the application of biochar contribute to the reduction of greenhouse gas emissions in sustainable farming practices?
2. What are the most critical opportunities and challenges of using biochar in sustainable farming?
3. What prospects and research directions are suggested for improving the role of biochar in climate-smart agriculture?

2 Climate Change Mitigation

During the 21st COP21 (United Nations Framework Convention on Climate Change) in Paris, socio-environmental challenges stemming from anticipated global warming impacts, such as heightened risks of flooding and droughts, were acknowledged. Deliberations are also engrossed in natural-based determinations to address these challenges, but in reality, the changing climate poses an imperative risk to soil fertility and plant environments [31]. Changes in climate patterns upset the convenience of essential nutrients in the soil, which are situated in declining soil fertility [32]. This decline in soil fertility has general consequences, affecting plant growth and inclusive ecosystem stability [33]. Furthermore, exciting meteorological conditions irregularity like drought and flood, impaired through climate change, increased soil degradation, and interrupt optimum plant growth [34]. In light of these complications, it is imperious for mutual investigators and agriculturalists to monitor soil environments attentively and change to suggested farming practices [35]. By smearing sustainable soil managing approaches and assuming climate-resilient agricultural stratagems, for instance, crop diversification and water management, subsequently alleviates the opposing outcome of global climate change on soil fertility and encourages longstanding farming sustainability [36].

Climate change mitigation comprises various actions projected to decrease/prevent the gas GHG emissions caused by human activities, consequently struggling with global warming [37]. The decrease in GHG emissions is overcome through sustainable ecosystem management, which is considered a decisive factor in the approaches expected to complete this objective. These efforts stand conclusive for mitigating the antagonistic effects of climate change. Several techniques are approved, including falling requirements on fossil fuels, which are noteworthy shares of GHG emissions [38]. This includes converting to harmless and more sustainable vigour sources such as astrophysical, wind, and hydro-electric [38]. The elevation of public policies and incentives that endorse implementing clean energy skills played a fundamental role in this conversion [39]. Presently, wetlands, cultivated land, and woodlands are essential as land-use types are accomplished to further appropriate carbon in soil biomass. These observations significantly impact plummeting atmospheric CO_2 levels and climate change mitigation [40]. Masson-Delmotte et al. emphasized that these ecosystems are crucial for achieving net-zero greenhouse gas emissions by 2050 and preventing global temperatures from rising above 2°C [41].

Biochar Characterization and Production

Plant-derived biomass primarily comprises plant fibres composed predominantly of carbohydrates [31]. Lignocellulosic biomass mainly consists of the biopolymer's hemicellulose, cellulose, and lignin, collectively comprising approximately 85% to 90% of its total mass, with the remaining portion composed of various extracts and minerals [42,43]. Yogalakshmi et al. provided a comprehensive review, highlighting that lignocellulosic biomass typically contains relative proportions of approximately 40%–60% carbon, 20%–40% hydrogen, and 10%–24% oxygen [44]. Lignocellulosic resources are viewed as a promising feedstock for biochar production because of their renewability, abundance, and less expensive nature [45]. Applying lignocellulosic waste to generate substances and biochar suggested dual benefits: it reduces residual biomass burning and repurposes waste biomass into valuable bio-oil and biochar products [46]. An estimated 500 million tons of agricultural residues are generated annually [47].

Consequently, waste lignocellulosic biomass was a primary source for producing biochar [48]. The elemental composition and the proportions of cellulose, hemicellulose, and lignin vary among different types of lignocellulosic biomass [49]. As a result, biochar made from other feedstocks showed various properties [45,50]. Biochar is produced from solid waste like agricultural biomass and sewage waste from treatment facilities [51]. Numerous materials have been used as biochar production feedstock, including tires, plastic waste, food crops, paper scraps, intrusive plant biomass, algae, diatoms, and municipal sludge [52]. Pyrolysis is a thermochemical process that includes degrading organic molecules without sufficient oxygen and producing pyrolytic oil, pyrolytic gas, and solid residue [53]. It is a widely adopted technology for producing biochar, involving three key processes: chemical transformation, heat transfer, and mass transfer. The physicochemical characteristics of the resulting biochar are influenced by both the feedstock type and the specific pyrolysis conditions [54]. There are eight main methods of pyrolysis used to produce biochar: fast, slow, co-, microwave, flash, vacuum, hydrothermal, and intermediate pyrolysis. Fig. 1 depicts the pyrolysis process of biomass into refined biochar, followed by various modification techniques. It also illustrated the complex interactions between biochar, compost, and soil properties, emphasizing key mechanisms such as enhanced nutrient adsorption, phosphorus desorption from clay surfaces, and the gradual nitrogen mineralization, which collectively contribute to sustained nutrient availability.

The properties of biochar (biological, chemical, and physical) are subjective to the original biomass's composition, structure, and internal bonding [57]. Researchers have concentrated on altering biochar properties during pyrolysis by employing various techniques. Factors such as pH, activation temperature, activating agents, and their concentrations play a crucial role in influencing the modification of biochar properties [58]. Lignocellulosic biomass, composed of lignin (16%–45%), hemicellulose (20%–40%), and cellulose (13%–50%), undergoes decomposition during pyrolysis, leading to the formation of aromatic compounds, including biochar [59]. According to Yogalakshmi et al., the optimal temperature range for maximum biomass decomposition is 200°C–400°C. Hemicellulose primarily breaks down between 200°C–280°C, cellulose degrades between 250°C–400°C, and lignin degradation occurs at higher temperatures, typically between 300°C–550°C [44]. Fig. 2 shows that biochar on soil hydrological properties.

Biochar is a carbon-rich substance commonly produced through the pyrolysis process, which involves the thermal decomposition of biomass at temperatures typically below 700°C [60]. This technique with crop residue deposit is recognized as biochar, characterized by highly carbon-contented and fine-grained texture [61]. Biochar production, derived from organic materials or agricultural by-products, is considered a carbon-negative process, effectively reducing atmospheric CO_2 levels [62].

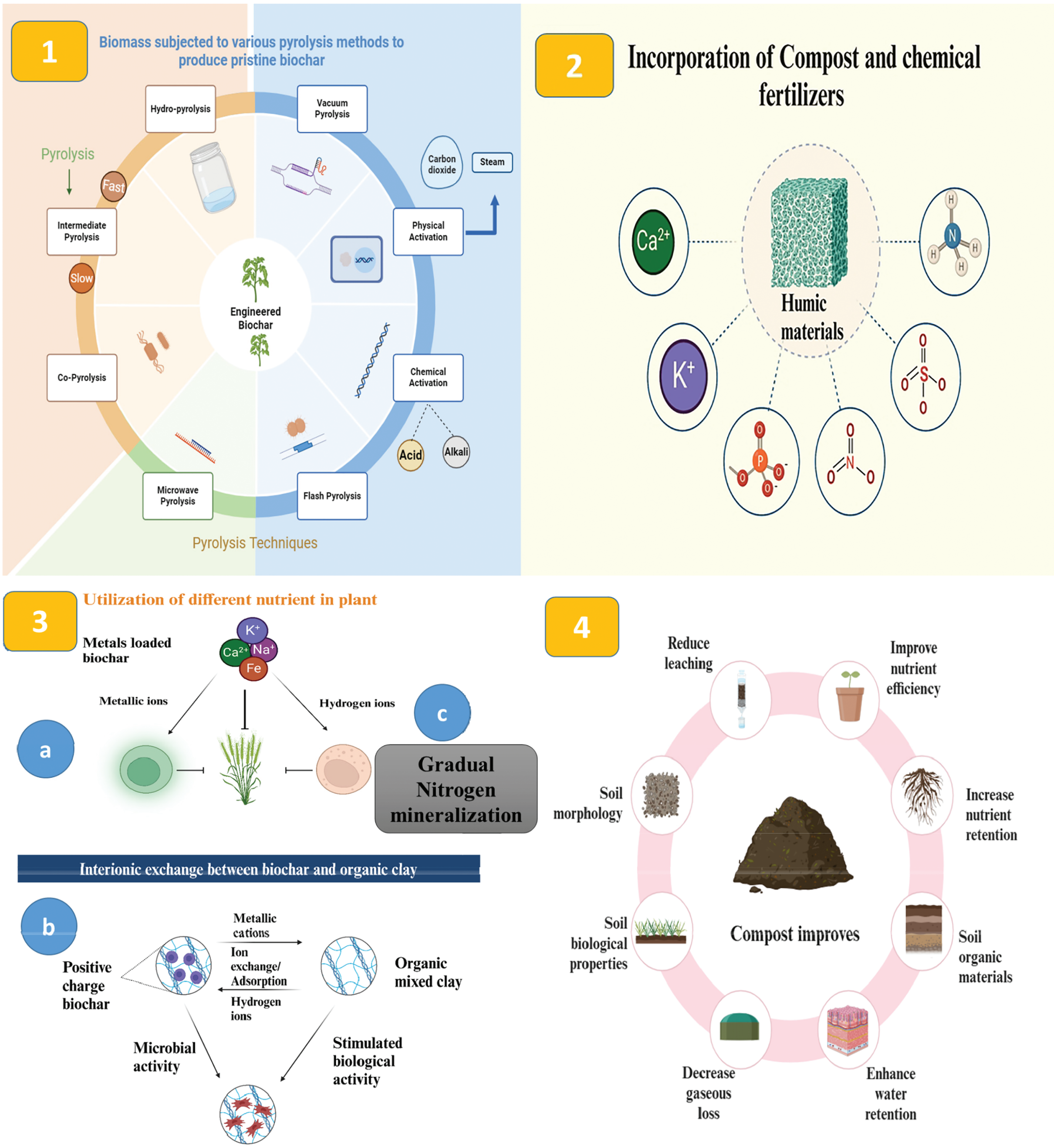

Figure 1: (1) Biomass undergoes pyrolysis through various methods to get purified biochar, which can be modified through physical, chemical, or advanced engineering techniques [55]. (2) Illustration of compost-amended soil showing humic acid's role in nutrient incorporation. (3a) Effective adsorption of plant nutrients at specific sorption sites, enhancing plant uptake through proton release. (3b) Mechanism of compost aiding in P molecule liberation from clay sorption sites. (3c) Gradual N mineralization in compost providing sustained nutrient availability. (4) Unique interactions between biochar, soil properties, and compost processes [56]

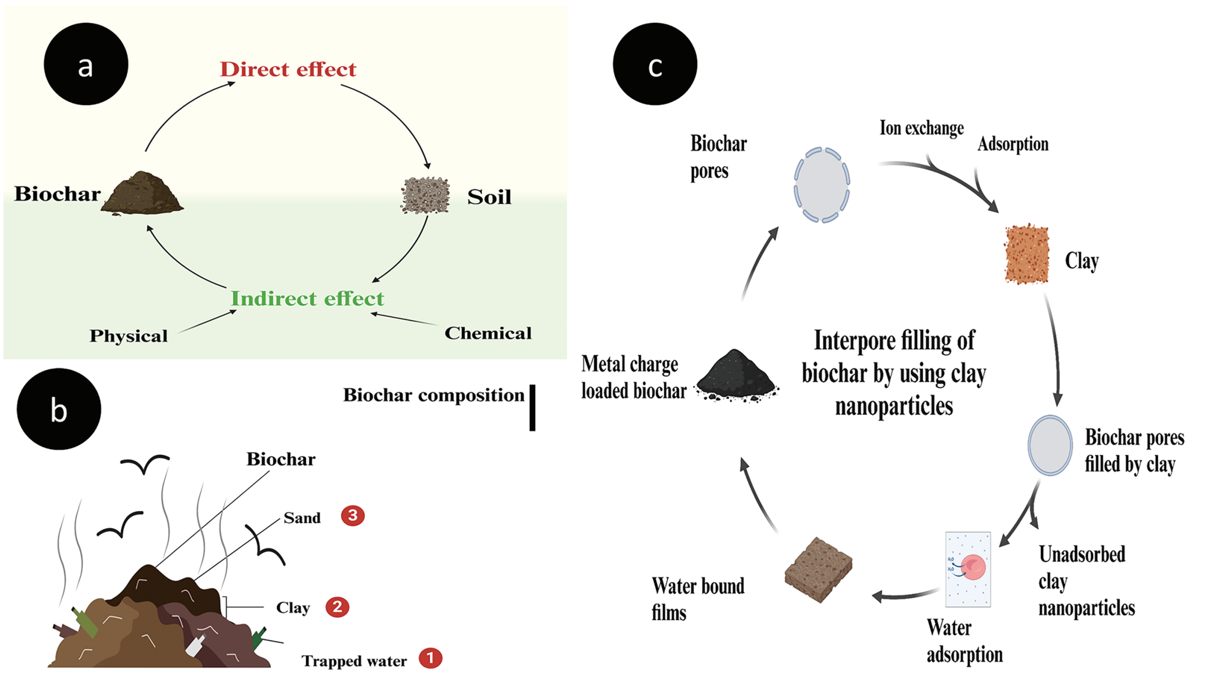

Figure 2: The influence of biochar on soil hydrological properties: (a) schematic; (b) direct effect; and (c) indirect effect [58]

Biochar is a carbon sink, appropriating carbon, water preservation, and nutrient-holding capacity in the soil [63]. Various methods produce biochar, including gasifiers, kilns, and other thermal decomposition techniques [64]. The resulting product is a cost-effective, highly aromatic solid rich in carbon, suitable for various applications [62]. Biochar has proven effective as a soil amendment, compost fertilizer, and energy source, particularly in agro-industrial sectors. Its production contributes to carbon mitigation, enhances soil quality, and promotes sustainable agricultural practices [65]. Fig. 3 illustrates the importance of biochar on different physicochemical and biological characteristics.

3 Biochar Role in Greenhouse Gas Reduction

Biochar is engaged in recreation, reducing greenhouse gas emissions, and has a predominantly role in nitrous oxide and carbon dioxide [66]. The foremost procedure by which biochar decreases GHG emissions is to improve soil nitrogen cycling and minimize nitrogen (N) fertilizer losses [67]. Ahmad et al. revealed that biochar adsorbs and retains various nitrogen compounds, reducing nitrogen leaching and volatilization and preventing the conversion of nitrogen into potent greenhouse gases like N_2O [68]. Furthermore, Duan et al. and Sapkota et al. further emphasized that biochar directly contributes to mitigating soil greenhouse gas (GHG) emissions [69,70]. Recent research has revealed that the assimilation of biochar soils decreased GHG emissions limited with the outcome size variable based on biochar application rates [71]. The carbon-sequestering properties assets of biochar also contributed to climatic change and mitigation potential [62]. Cowie et al. explained that incorporating biochar produced from plant-based biomass into soils removes atmospheric carbon dioxide stored in the soil, compensating for fossil fuel emissions [72]. The judicious use of biochar reduces GHG emissions and climate change combating strategy. Table 1 provides an overview of biochar's long-term impact on mitigating GHG emissions in soil. Biochar is a natural resource that can significantly reduce greenhouse gas emissions, particularly in the form of nitrous oxide and carbon dioxide. It improves soil nitrogen cycling, minimizes nitrogen fertilizer losses, and reduces nitrogen leaching and volatilization. Biochar's carbon-sequestering properties contribute to climate change mitigation potential. Incorporating plant-based biomass into the soil removes or eliminates atmospheric carbon dioxide, compensating for fossil fuel emissions. The judicious use of biochar is successful in reducing GHG emissions.

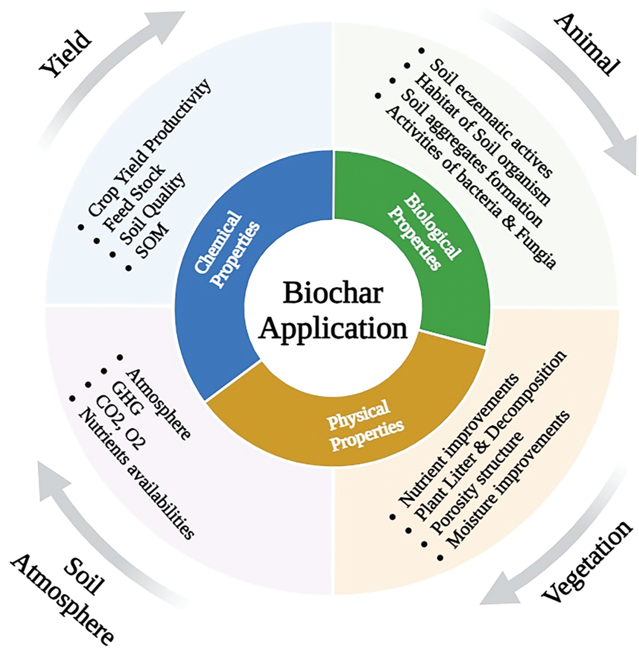

Figure 3: Effect of biochar on different physical, chemical, and biological properties

3.1 Carbon Dioxide

Carbon sequestration and mitigation are crucial in addressing climate change [81]. According to [82], Carbon sequestration is described as increasing the carbon content in a carbon reservoir excluding the atmosphere. Moreover, carbon sequestration in soil is defined by [83] as the "process of transferring CO_2 from the atmosphere into the soil of a land unit through plants, plant residues and other organic solids, which are stored or retained in the unit as part of the soil organic matter (OM)" biochar can sequester carbon [84]. The interaction between soil particles and organic carbon leads to minimal CO_2 emissions from the soil, lowering greenhouse gas emissions and mitigating climate variation [75,85]. When added to soil, biochar acts as a carbon sink, making it a carbon-negative amendment [62]. CO_2 reduction by biochar involves capturing carbon and storing it in the soil, which can potentially mitigate 10% of anthropogenic carbon emissions with just a 1% increase in net annual carbon sequestration by plants [86]. By 2030, it is estimated that biochar could sequester nearly 1 billion tons of carbon annually [87]. Puga et al. showed that adding biochar, such as rice husk biochar, to specific soils in maize plantations effectively reduces CO_2 emissions [88].

Similarly, corn stover and rice husk biochar have been shown to reduce soil CO_2 emissions over time, with 1 ton of biochar capable of sequestering 2.0 to 2.6 tons of CO_2 from the environment [89]. Carbon sequestration and mitigation are crucial in addressing climate change. Carbon sequestration in soil involves transferring CO_2 from the atmosphere into soil through plants and organic solids. When added to soil, biochar acts as a carbon sink, reducing CO_2 emissions and mitigating climate variation. By 2030, biochar could sequester nearly 1 billion tons of carbon annually. Adding biochar to maize plantations reduces CO_2 flux and decreases soil emissions over time. Applying 1 ton of biochar could sequester 2.0 to 2.6 tons of CO_2 from the environment [75,85].

Table 1: Summary of research on biochar's long-term impact on mitigating GHG emissions in soil

Biochar types	Pyrolysis temperature	Plant/ Crops	Rate of biochar	Soil texture	Study area	Decline in GHS emission rate (% age)			Duration	References
						CO_2	N_2O	CH_4		
Rice straw	500°C	Rice	250 kg ha^{-1}	Paddy soil	China	___	30.56%	27.80%	1 year	[73]
Wheat straw-derived biochar	500°C	Rice-wheat	40 t ha^{-1}	Silty clay loam	China	___	33.6%	20.9%	3 years	[74]
Corn residue-derived biochar	400°C–500°C	Corn	30 t ha^{-1}	Sandy loam	China	18%–25% (1st growing season) & 19%–41% (2nd growing season)	71%–110% (1st growing season) & 39%–47% (2nd growing season)	132%	2 years	[75]
Manure-derived biochar & wood residue biochar	550°C	*Sorghum sudangrass*	11 t ha^{-1}	Andisol	Chile	No significant impact	23%–50%	__	1 year	[76]
Leftover rice straw-derived biochar	500°C	*Rice*	3 t ha^{-1}	Tropical paddy soil	Thailand	37.4%	___	42.9%	5 years	[77]
Wheat straw-derived biochar	450°C	*Barley*	20 t ha^{-1}	Black Chernozemic soil	Canada	27.2	50.9%	No significant impact	2 years	[78]
Wheat straw-derived biochar	500°C	*Rice*	48 t ha^{-1}	Ultisol	China	___	24%	29%	4 years	[79]
Wheat straw-derived biochar	500°C	Rice-wheat	40 t ha^{-1}	Silty clay loam	China	___	18.7%	9.3%	6 years	[80]

3.2 Methane

Methane (CH_4) emissions from crops justify almost all overall CH_4 emissions and anthropogenic global warming 3%–15% and 8%–16%, respectively [90]. Soil microbes are essential in CH_4 emissions via methanogenesis under anaerobic conditions [91]. Methane has a higher approximately (20 times greater) global warming potential than CO_2 [92]. Research has reported that incorporating biochar as a soil amendment significantly decreases CH_4 emissions [77]. For example, zero CH_4 emissions were observed when biochar was applied to soil at a rate of 2% [93]. Accumulating rice straw biochar [73] and bamboo chip biochar [94] in the paddy soil also decreased CH_4 releases. Moreover, biochar-amended as a soil-based proved to reduce CH_4 emissions [95] and improve water-holding-capacity (WHC) compared to unprocessed soil [96]. Opposing findings that demonstrated a decline in methane emissions, Reference [95] studied the effect of biochar application on GHG fluxes in Mediterranean wheat cropping and found no outstanding alterations in methane changes among the different biochar treatments applied compared to without biochar application. The quantity of CH_4 released depends on several factors, such as (a) soil type and condition [97], (b) microbial activity [98], (c) Water and fertilizer practices [99], and (d) physicochemical properties of biochar [66].

Biochar-amended based soil performed as a source-sink used for atmospheric CH_4 [100], influenced via soil moisture [101], daytime root respiration affected [102], and further microbial activities in Soil [103] that affect soil oxygen levels. Administrating rice husk biochar in paddy fields lessens methane emissions by 80% compared to untreated soil [104]. Adding biochar improves compost structure by reducing anaerobic spots [105]. Garg et al. noted that biochar enhances soil permeability [106], while Sriphirom et al. highlighted its impact on the oxidation-reduction potential due to biochar electron-accepting capacities (EAC), which decreases methanogenic activity and increases methanotrophic activity, ultimately reducing CH_4 emissions [107].

Wu et al. described biochar surfaces as rich in oxygen-based functional groups, including carbonyl, carboxyl, phenolic, quinone, and hydroxyl groups [108]. Kamal et al. emphasized that oxygen-containing functional groups, particularly quinone and carbonyl, are crucial for biochar's redox properties, as they accept electrons, influencing its EAC [109]. Similarly, Zhang et al. found that biochar facilitates anaerobic CH_4 oxidation through its quinone structure (C=O) [110], while Nan et al. suggested that biochar may mitigate CH_4 emissions by enhancing anaerobic CH_4 uptake via its EAC in the soil [111]. Additionally, biochar, with an aromatic structure characterized via coupled π-electron-systems, facilitated CH_4 ingesting in soil accomplished acting electron acceptor. Furthermore, biochar adsorbed NH_4^+, reducing the nitrogen (N) accessible to methanogens and deterring their activity, which sinks CH_4 emissions [105]. This adsorption minimized the inexpensive hang-up of methane-monooxygenase by NH_4^+−N, enhancing the methanotrophs oxidation and plummeting CH_4 emissions [112]. Biochar-amended soil also improved water-holding capacity compared to unprocessed soil. Several factors, including soil type and condition, microbial activity, water and fertilizer management, and the physicochemical properties of biochar, influence CH_4 emissions [97]. Overall, biochar-amended soils can act as a source-sink for atmospheric CH_4, with performance impacted by soil moisture, daytime root respiration, and microbial processes within the soil. It also improves compost structure, increases soil permeability, and affects oxidation-reduction potential.

3.3 Nitrous Oxides

Cultivated soil is a primary source of N_2O emissions, accounting for 67% of total anthropogenic emissions [113]. Research has revealed that approximately 10%–23% of N_2O emissions occurred in high moisture (80%) levels compared to low moisture (40%) levels in soil [114]. The usage of biochar to reduce N_2O emissions from farming soil has been expansively investigated [115]. For instance, it was observed that adding 10% biochar to soil reduced N_2O emissions by 89% compared to untreated soil [116]. Applying straw-resulting biochar with highly carbon-to-nitrogen (C:N) ratios immobilized nitrogen fertilizers, decreasing nitrogen accessibility and reducing N_2O emissions from the soil [73]. Nitrogen (N) fertilizer is a prime and common source of N_2O emissions from farming soil. Research has shown that biochar Soil amendments have reduced these emissions [72]. In Colombia and North America, greenhouse and field research observed an 80% reduction in N_2O emissions when biochar treatments were applied to the soil [117]. Similarly, results were obtained with a 77%–82% decrease in N_2O emissions in pot experiments reported for vegetable production, higher nitrogen (N) fertilizer rates were applied with biochar, and higher moisture content was observed [118].

Biochar improved the activity of N_2O reductase, an enzyme that reduces N_2O emissions by altering nitrate to N_2, mainly as soil pH increased [119]. Furthermore, biochar performed as an "*electron shuttle*" expediting electron transfer over denitrifying microbes activities, which reduced nitrous oxide towards nitrogen [120]. However, biochar application management to Calci-sol soils caused elevation in N_2O emissions (54%) reported by [25]. Overall, biochar application at lower rates (2%–10%) effectively reduces N_2O emissions, and higher application rates with reductions were observed at 63% and 74%, respectively [121]. Cultivated soil is a significant source of N_2O emissions, accounting for 67% of total anthropogenic emissions. Biochar has been investigated as a potential solution to reduce N_2O emissions from farming soil. Studies show that adding 10% biochar to soil reduces N_2O emissions by 89% compared to untreated soil. Applying straw-resulting biochar with high carbon-to-nitrogen ratios immobilizes nitrogen fertilizers, decreasing nitrogen accessibility and reducing N_2O emissions [117] Biochar also improves the activity of N_2O reductase, reducing N_2O emissions by altering nitrate to N_2. However, biochar application to Calcisol soils can increase N_2O emissions [72].

4 Soil Fertility Enhancement through Biochar

Biochar is frequently employed in soil amendment because of its distinctive physico-chemical characteristics [122]. Amending soil with biochar significantly impacts its physico-chemical [123] and biological (microbial) properties [43]. Fig. 4 shows the interlinkage between biochar and soil health system. Biochar is a fertilizer that improves soil fertility and reduces pollution [124]. The primary assays influencing the soils physico-chemical and biological environment are critical properties of biochar, such as chemical composition, pH, porosity, electrical conductivity, Soil surface area, available nutrient content, and nutrient exchange value [43]. Biochar is a popular soil amendment due to its unique physico-chemical characteristics [123]. It significantly impacts soil fertility and reduces pollution [125]. Critical properties of biochar include chemical composition, pH, porosity, electrical conductivity, SSA, nutrient content, and nutrient exchange value, influencing the soils physico-chemical and biological environment [126].

5 Modifications in Soil Physical Attributes Induced by Biochar Inclusion

Positive qualities of biochar administration on soil physical morphologies have been reviewed. For instance, adding biochar to soil significantly impacts porosity and bulk density [127] and improves the surface area and soil aeration [128]. Additionally, biochar utilization directly modifies the soil and water by elevating soil aggregation, stability, workability, and water infiltration and increases WHC [126]. Biochar influences the physico-chemical properties of contaminated soil, with effects depending on the soil type [123], feedstock [129], application rate [125], and the ageing of biochar [130]. For example, adding 4% biochar to soil can minimize soil bulk hardness by up to 35% [131]. In experimenting with Alfisol and Andisol soils having (silt-loam) texture, the application of biochar at a rate of 7.18 t C ha^{-1} decreased the bulk density of Alfisol soil by 7% used for biochar produced at 350°C and through 11% for biochar produced at 550°C. Nevertheless, no decline in bulk density remained for Andosol soil [132].

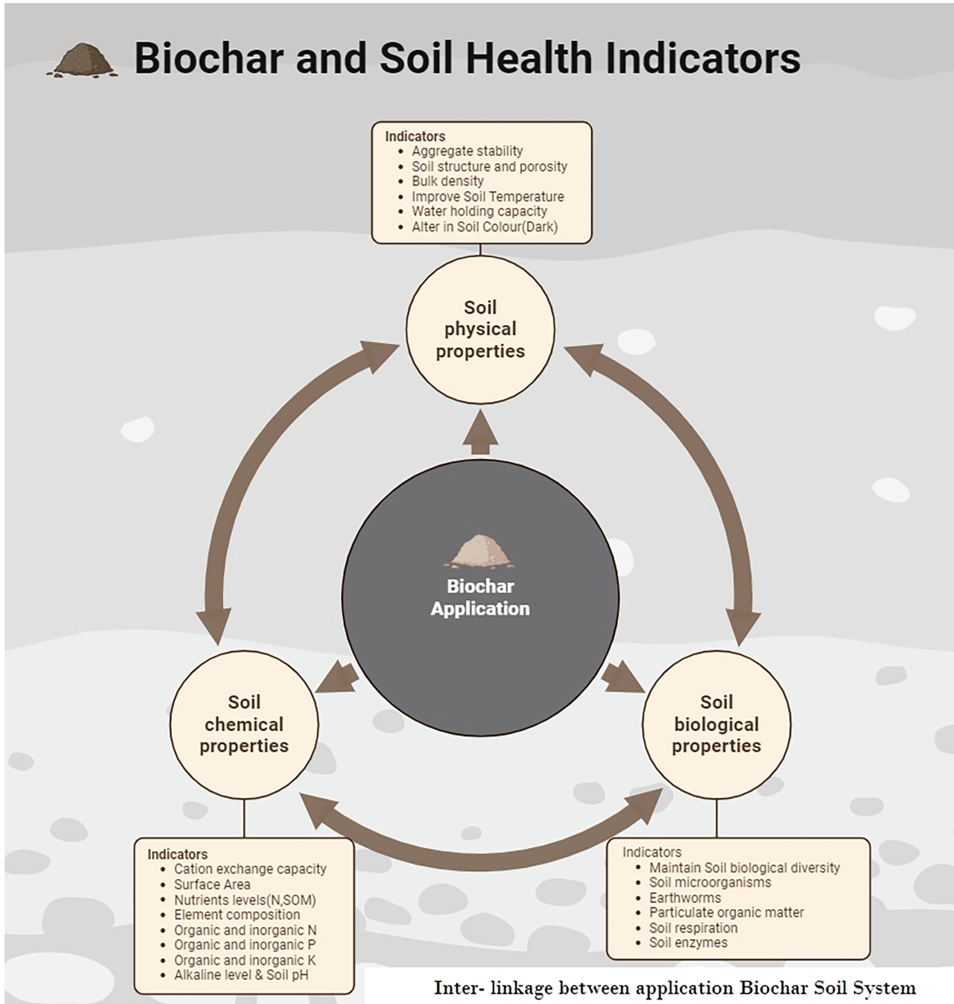

Figure 4: Inter-linkage between biochar application and soil health system

Luo et al. reported no changes in soil density following adding biochar [133]. However, Murtaza et al. noted that changes in bulk density can result from factors such as the porosity of the biochar [134]. Similarly, Ferraro et al. highlighted that variations in biochar structure and pyrolysis conditions also influence bulk density [135,136]. Biochar has the potential to increase soil porosity by reducing bulk density [134], endorsing soil precipitation [137], inter-relating with soil minerals [134], and alleviating soil compaction [138]. Reduction in bulk density and elevation of soil porosity facilitates enhanced heat, water, and gas movement in soils, ultimately improving soil quality [139]. Table 2 shows an overview of the modifications in soil physicochemical qualities resulting from biochar amendment. Biochar administration has positively affected soil physical morphologies, such as porosity, bulk density, surface area, and soil aeration. It also directly modifies soil and water by elevating soil aggregation, stability, workability, and infiltration and increasing water-holding capacity. However, no changes in density were observed after biochar incorporation. Biochar can also increase soil porosity by reducing bulk density, endorsing soil precipitation, inter-relating with soil minerals, and alleviating soil compaction.

Table 2: Summary of studies on biochar impact on crop yield and soil properties

Crops	Soil type	Experiment type	Biochar type	Positive consequences	Location	Reference
Maize	Sandy loam	Pot	Cow manure	The soil's water-holding capacity was increased by 1.5% by mass for each 1% biochar added. High germination % in pots having 1% of biochar.	Pakistan	[140]
Cotton	Saline-alkali	Pot	Rice straw	Enhanced soil physio-chemical properties (e.g., available potassium, SOM, and exchangeable potassium). Promoted plant development and remarkably increased its biomass.	China	[125]
Wheat and maize	Silt loam	Field	Straw-derived biochar	Significant increase in SOC, total nitrogen, microbial biomass carbon, and nitrogen in the soil surface layer. Significant increase in plant height and aboveground biomass.	China	[141]
Tobacco	Silty loam	Field	Straw	Soil pH, SOC, available nutrients, soil urease, invertase, and acid phosphatase activities increased. The agronomic traits of tobacco were improved by biochar treatment.	China	[142]
Wheat	Red soil (Ultisols)	Pot	Wood	Efficiently alters soil pH and EC and reduces the bioavailability of toxic metals (Zn, Pb, Cd & Cu) in soil. It improved wheat dry biomasses production.	China	[143]
Corn	Oxisol	Field	Sewage sludge	Promoted a residual effect on the supply of soil nutrients. Available P content remained above the minimum level required by the corn crop.	Brazil	[144]
Wheat	Sandy loam	Pot	Sewage sludge	Significant increase in soil P availability and soil pH.	Denmark	[145]
Okra	Alluvial	Field	Rice Husk Biochar (RHB), Bamboo Biochar	Physical properties of soil (e.g., bulk density, soil porosity, particle density) and fruit size & yield of okra were remarkably improved. ALB significantly	Nepal	[146]

(Continued)

Table 2 (continued)

Crops	Soil type	Experiment type	Biochar type	Positive consequences	Location	Reference
			(BB), Ashoka Leaf Biochar (ALB), Coconut Husk Biochar (CHB), Sawdust Biochar (SB)	reduced bulk density (10.9%), increased soil porosity (10.6%), and gave the highest fruit yield (8.16 t ha^{-1}). SB showed the highest reduction in soil particle density (4.4%), and BB gave the most prominent fruit size (15.7 cm) among all the treatments.		
Brassica rapa	Sandy loam	Pot	Rice husk	Increased soil pH, organic carbon content, and water holding capacity and reduced bioavailability of trace elements. Increased germination of *Brassica rapa*.	Spain	[147]
Tomato	Sandy loam	Pot	Rice husk	An appreciable increase in soil physicochemical properties (pH, Ca, H^+, Na, S, P, C, B, Zn & CEC). Significant increase in tomato agronomic traits (height, weight, leaf area, stem girth, flowers, fruit & yield).	Nigeria	[148]

6 Modifications in Soil Chemical Attributes Induced by Biochar

Adding biochar to soil has the moral potency to modify pH levels. Minor pH in the soil leads to toxicity, primarily due to the augmented availability of heavy metals [145]. Some biochar is characteristically alkaline (pH > 7) when applied to soil raised soil pH [149]. Biochar pH influences the feedstock and ranges from acidic to alkaline in nature [150]. In acidic soils, biochar alkaline properties significantly mitigated soil acidity, thus enhancing soil properties and conditions [139,151]. For example, biochar synthesized from several farming wastes has been visualized to improve soil pH [152]. The addition of corn stover-based biochar with rice husk at a rate of 3% was observed to raise the soil pH significantly [89] in acidic soils based on Alfisol, management of plant-green-waste biochar with poultry litter at rates of 10 to 100 t ha^{-1} improved soil pH [132]. Studies have proven a two-fold improvement in soil pH in various acidic soil types compared to the actual pH through biochar application [153].

The CEC of biochar indicated that several cations adsorbed on its surface [154]. Some factors, such as pyrolysis conditions, soil temperature, feedstock material [135,155], and efficient functional groups [156], determine the CEC of biochar. For instance, straw-derived biochar prepared at 450°C exhibited a CEC of 26.36 cmol kg^{-1}, which decreased to 10.28 cmol kg^{-1} at 700°C [25]. Studies have demonstrated that CEC remains low until temperatures exceed 420°C due to changes in the feedstock's nutrients [154].

High CEC facilitates the withdrawal of heavy metals from contaminated soil [141]. Soil pH elevation after biochar addition has been observed to enhance soil CEC [157]. However, adding biochar to soils with high OM content may not increase CEC significantly since OM already contributes to a greater CEC [158]. Additionally, enough Organic Carbon Functional Groups (OCFGs) on the biochar surface contribute to surface charge, enhancing soils CEC following biochar administration [159]. Fig. 5 shows that the biochar improved the soil's properties.

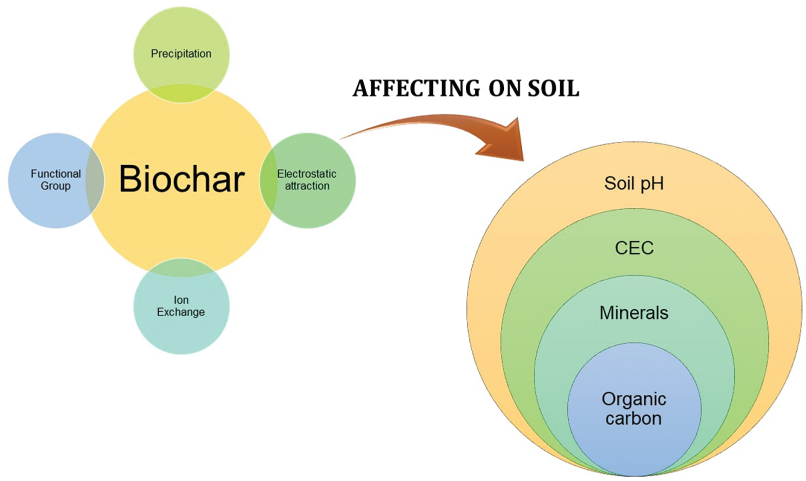

Figure 5: Features of biochar influencing the soil properties [160]

The stability and quantity of biochar applied in soil amendment are essential in increasing soil OM [125]. Biochar, rich in minerals like N, K, P, Ca, S, and Mg, can enrich soil nutrient levels and enhance productivity [161]. It improves soil cation levels (K, Cu, Mg, Mn, Ca, Zn) and is vital for plant development [162]. Studies revealed that biochar catalyzes surface reactions, aiding in polymerization for organic molecule formation and creating macropores for minor organic molecule adsorption in soil [163]. The increase in soil OM content impacts crop yield positively due to enhanced soil porosity [146], improved nutrient activity [142], and reduced soil bulk density [134].

Nitrogen availability is crucial for plant growth but is susceptible to significant volatilization, denitrification, and leaching [67]. Biochar enriches soil nitrogen retention through OCFGs such as aliphatic ether, aromatic ring carbonyl, and hydroxyl [164]. Maize biochar addition accelerates soil nitrogen content by promoting net N mineralization, enhancing nitrification, and reducing NH_3 volatilization [165]. Nelissen et al. compared different types of biochar synthesized at various temperatures, and it was found that lower-temperature biochar (350°C) increased gross mineralization and labile nitrogen fraction compared to high-temperature biochar at 550°C [166]. Additionally, biochar supplementation accelerates the nitrogen cycle, increasing gross mineralization, nitrification, and NH_4^+ consumption rates. This is attributed to enhanced soil porosity/aeration and biochar stimulation of the heterotrophic or aerobic microbial community [165].

Biochar application influences plants' soil phosphorus (P) availability through factors like charge exchange capacity that bind P [144]. Phosphate composites form in the soil at varying pH levels, with biochar preventing phosphate precipitation and enhancing P availability to plants [167]. Field studies on maize demonstrated that biochar incorporation improved available P, increasing maize yields [168]. Furthermore, biochar application has been explored to enhance P availability for plants, even in soils with low P availability. Fig. 6 illustrates various adsorptive capacities of N and P ingredients by biochar. Biochar enriches soil nitrogen retention through OCFGs, such as aliphatic ether, aromatic ring carbonyl, and hydroxyl. Maize biochar addition accelerates soil nitrogen content by promoting net N mineralization, enhancing nitrification, and reducing NH_3 volatilization. Biochar application also influences plant soil P availability through factors like charge exchange capacity. Field studies on maize have shown that biochar incorporation improves available P, increasing maize yields.

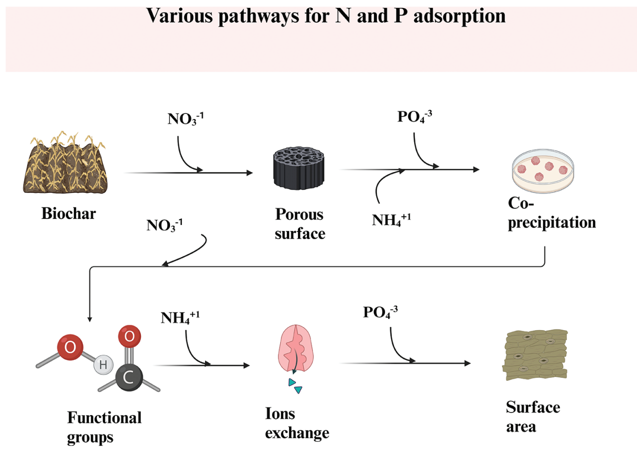

Figure 6: Various adsorptive capacities of N and P ingredients by biochar and data adopted from [169]

7 Modifications in Soil Microbial Community Attributed to Biochar Integration

Biochar integration into soil significantly modifies microbial communities, which is crucial for enhancing soil health and promoting sustainable agro-ecological practices [170]. Microbial communities are highly responsive to environmental changes, making the impact of biochar addition on species reactions a subject of extensive study in various environments [171]. Biochar administration to soil can directly or indirectly impact microbe's community composition and function by providing them habitat, nutrients, and large surface areas [172]. Additionally, biochar can alter soil pH, often making it more alkaline, which influences the composition of microbial communities by favouring specific taxa like *Nitrosomonas* and *Nitrobacter* [173], which are essential for nitrification processes [174]. Microbes can attach to biochar micropores through electrostatic forces, precipitate formation, or hydrophobic attraction, becoming less prone to leaching and rising prevalence [175]. However, some investigations suggested that certain biochar micropores may be too small to support microbial colonization [176].

Nevertheless, these micropores can still adsorb organic materials, nitrate, and NH_4^+, fostering microbial growth and development [169]. Biochar porosity promotes soil aeration and water retention [177], which is crucial for the endurance of numerous microbial species [172] involving rhizospheric bacteria and other edaphic organisms [42,43]. Biochar demonstrates a range of effects, both positive and negative. It can potentially have toxic properties on soil bacteria and provide significant benefits such as augmenting attractions with plant roots, helping biological mature processes, supporting the degradation of pollutants, and stabilizing carbon complete micro aggregation [178]. Furthermore, biochar's ability to improve soil porosity and aeration produces a more favorable environment for microbial growth, particularly in arid regions [179]. Some studies also suggest that biochar suppresses soil-borne pathogens, such as *Fusarium* and *Rhizoctonia*, through enhanced microbial competition or the production of antimicrobial compounds [180]. Hence, the integration of biochar not only modifies soil microbial dynamics but improves their effectiveness in promoting soil health and fertility, underscoring its potential in sustainable agricultural systems [181].

Recent research indicates that biochar improves soil structure, water retention, and nutrient availability [182], increasing microbial diversity and activity—beneficial microorganisms such as *Bacillus* [42]. Biochar application often promotes *Pseudomonas* and Arbuscular Mycorrhizal Fungi (AMF), which are vital in nutrient cycling and soil fertility [183].

Moreover, biochar application has shown that assistance for biological nitrogen fixation in leguminous crops is influenced by mechanisms such as N immobilization and nodulation [184], increasing P source, and pH modification [185]. Fig. 7 depicts the effect of biochar on soil organic matter decomposition and nutrient absorption.

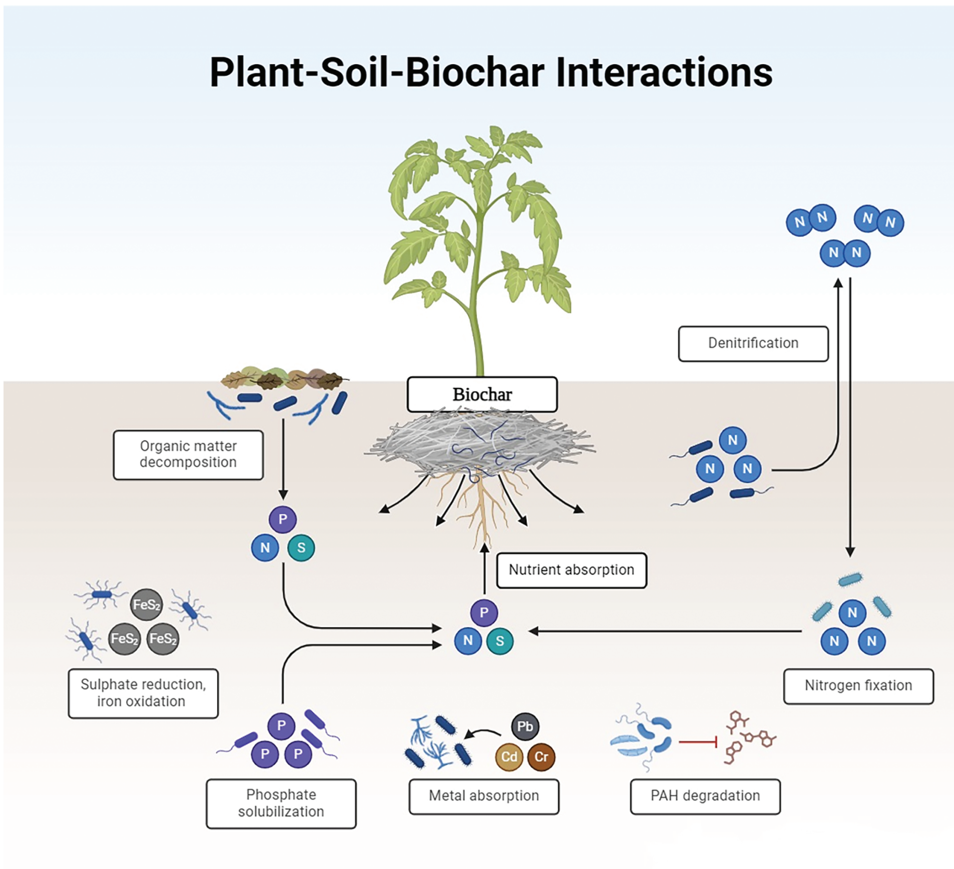

Figure 7: Effect of biochar on soil organic matter decomposition and nutrient absorption

Kamal et al. observed that the use of biochar, either alone or in combination with phosphorus (P), led to an increase in microbial populations, as well as the biomass of carbon (C), nitrogen (N), and phosphorus (P), while also enhancing enzymatic activities [109]. Alterations in the availability of resources, water content, and physio-chemical factors lead to alterations in microbial-based community structure and composition [184]. Diverse issues have been elevated regarding the potential deleterious influences of biochar to go to extreme usages, such as delaying microbial-based growth by interesting toxins like pesticides and heavy metals [186]. Moreover, many nutrient conversions are caused by soil microbial populations, affecting crop development [187]. Depending on soil conditions and the specific properties of biochar used, it negatively affects soil microbial populations and diversity. This is attributed to polyphenols and phenolic substances in biochar, which are by-products of organic pyrolysis and toxic to soil microbes. Some studies have observed reduced mycorrhizal and total microbial biomass following biochar application precisely. Combining peanut shell biochar significantly reduced arbuscular mycorrhizal fungi root colonization and length of mycelial spore by 74% and 95%, respectively [188].

Similarly, in maize field research, biochar applications harm soil microbial activity and community structure and function in alkaline soil [189]. These results contradicted. However, fresh biochar has decreased the mobility and availability of organic pollutants [186]. Moreover, research by [190], suggested that alterations in soil structure and texture resulting from biochar application affected microbial function and community structure in various ways.

Further research is required to evaluate the specific impacts of biochar on different soil and biochar types. Fig. 8 illustrates the effect of biochar application on improving beneficial microbes in agroecosystems, which impact plant growth and vitality. Biochar addition to soil can impact microbial communities by providing a conducive habitat, nutrients, and large surface areas that support microbial activities. For instance, soil pH, moisture level, and temperature can influence microbial diversity, population, and activity.

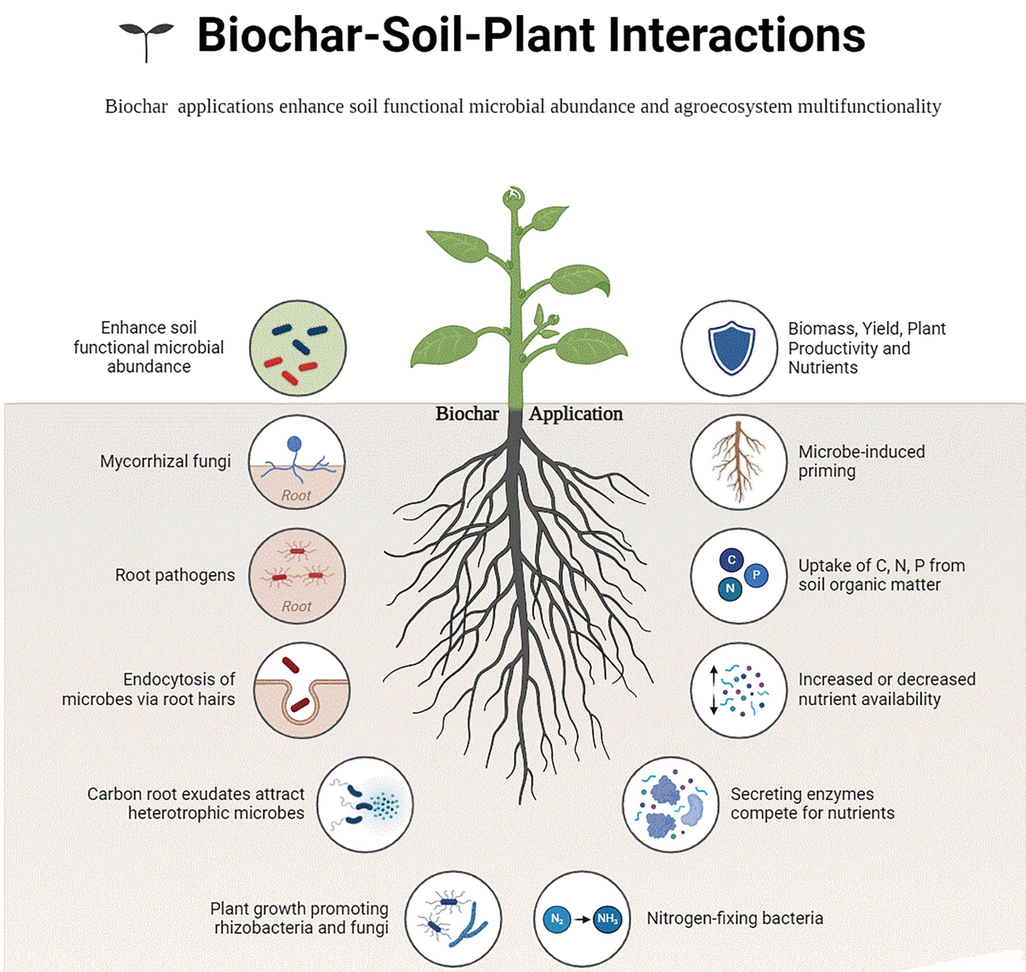

Figure 8: Effect of biochar application to improve functional microbes and agro-ecosystems

Moreover, soil microbial populations cause nutrient decomposition, which affects crop growth and development. Polyphenols and phenolic substances in biochar can adversely affect soil microbial populations due to their toxicity. Further research is needed to evaluate the specific impacts of biochar on different soil and biochar types.

8 Biochar for Plant Growth and Crop Yield

The agricultural field significantly contributes to atmospheric GHG emissions [191]. Biochar in soil can indirectly increase nutrient use efficiency (NUE) and water retention, leading to energy saving, reduced irrigation frequency, and decreased fertilizer use. This indirectly contributed to lowering GHG emissions [192]. Biochar utilization as a soil amendment has been displayed in various studies that have improved soil properties and increased crop yield [193]. Biochar is a nutrient reservoir, minimizing leaching and enhancing plant nutrient availability. Additionally, it positively influences soil microbial communities by promoting the growth of beneficial bacteria that aid in nutrient digestion, ultimately contributing to improved plant health [194,195]. Furthermore, biochar promotes symbiotic connections with mycorrhizal fungi, which boost the absorption of nutrients by plant roots, thus improving the overall biodiversity of soil [153]. In less fertile soils, biochar application led to a significant boost in crop productivity [196]. For instance, the maize yield maximum in Kenyan soil doubled after applying eucalyptus biochar [197]. Similarly, cow manure-derived biochar increased maize production by approximately 150% in sandy soil conditions [198]. Other studies demonstrated notable increases in wheat grain yield and peanut production after biochar application [194,195].

Hongjun et al. observed through pot experiments with sorghum grown in sandy desert soil that adding biochar significantly increased dry weight [199]. Figueredo et al. conducted field experiments with maize and common beans using biochar derived from eucalyptus charcoal, which confirmed notable yield increases [200]. These findings underscore the biochar capability as a soil enhancer for improving agricultural productivity. In numerous scientific studies, biochar has been shown to enhance crop yield by approximately 20% when applied at rates exceeding 10 tons per hectare [201]. Even at lower application rates, such as 5 tons per hectare, biochar can improve crop yields by up to 50% in specific soil types [202]. This improvement in crop yield is attributed to the positive changes in soil's physical, chemical, and biological properties resulting from biochar application [134]. The efficiency of biochar in boosting plant productivity varies depending on factors like climate [203], soil type, crop species, and experimental conditions [204]. Generally, biochar tends to be more effective in pot experiments compared to field trials [205], in acidic soils compared to neutral ones [206], and in sandy soils than loam and silt soils [207].

9 Contaminant Immobilization by Biochar: Applications and Factors Influencing Efficiency

Biochar, derived from organic matter via pyrolysis, holds promise for immobilizing and remediating various contaminants, such as heavy metals [208] and organic compounds [209]. Its surface area and porous structure enable effective adsorption and binding of pollutants, reducing their bioavailability and mobility [210]. The latest studies highlight the efficacy of base-treated biochar, especially from broiler litter, in immobilizing heavy metals due to modified surface properties [211]. Moreover, biochar-based materials can simultaneously immobilize multiple contaminants, making them suitable for remediating complex, multi-metal contamination [212]. Beyond heavy metals, biochar can potentially eliminate organic pollutants like pesticides through adsorption and microbial-based processes [213]. The effectiveness of biochar for contaminant immobilization is highly dependence on production conditions [214], contaminant types [215], and soil/water characteristics [216]. Biochar presents a promising approach for remediating contaminated assays such as soil and water environments, offering a versatile solution for addressing diverse pollutants [217]. Biochar exhibited, in effect, contaminant immobilization over several mechanisms. Because of its higher surface area besides its porous structure, it supports physical adsorption by binding contaminants resembling heavy metals via processes such as hydrogen bonding and electrostatic interactions [218].

By increasing soil pH levels and giving sites for precipitation reactions, biochar promotes the chemical precipitation of heavy metal contaminants [219]. The different functional groups on the biochar surface easily facilitate cation exchange, supporting the immobilization of cationic heavy metals [210]. Furthermore, biochar organic combinations of compound arrangements establish complexes by contaminants, which causes increasing immobility and bioavailability [220]. Moreover, biochar facilitates reducing pollutants and converting them into less toxic and mobile forms in a particular situation. These mechanisms' steps communally highlighted biochar efficiency in soil and remediation in water [221]. Biochar, derived from organic matter through pyrolysis, is promising for immobilizing and remediating contaminants like heavy metals and organic compounds [208,222]. Its surface area and porous structure enable effective adsorption and binding, reducing bioavailability and mobility [223]. Biochar-based materials can also immobilize multiple contaminants, making them suitable for complex, multi-metal contamination [224]. It also has the potential to eliminate organic contaminants like pesticides through adsorption and microbial-based processes [213]. Biochar's effectiveness depends on production conditions, contaminant types, and soil/water characteristics. Fig. 9 shows schematic representation of the nature of organic pollutants and their degradation using nZVI/BC-AOPs [225].

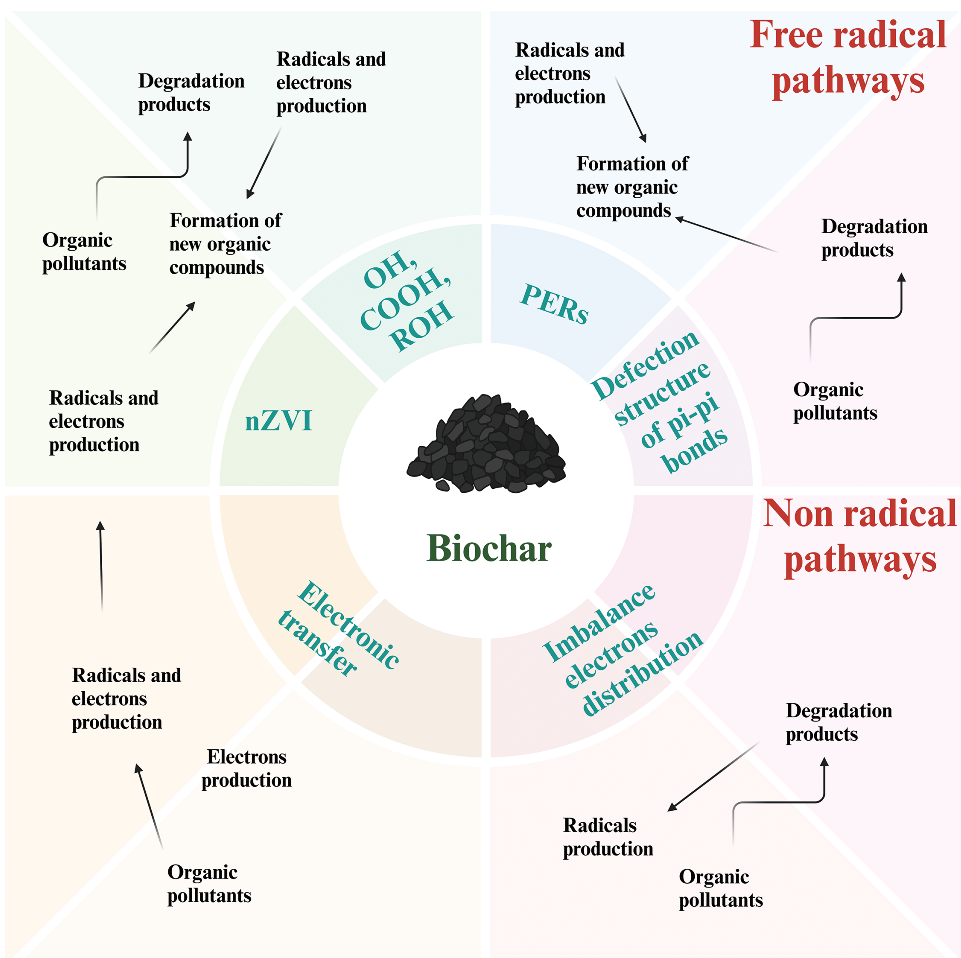

Figure 9: Schematic representation of the nature of organic pollutants and their degradation using nZVI/BC-AOPs [225]

Biochar offers a promising solution for immobilizing contaminants in polluted soil and water, including HMs and organic pollutants. The process involves multiple mechanisms: It has a vast surface area of abundant functional groups, and biochar effectively adsorbs and binds heavy metal ions and organic contaminants [218]. Due to the nature of organic acids and other biochar surface functional groups achieved unchanging composites with metal ions and decreased their bioavailability [220]. Biochar application elevates soil pH, reducing the solubility and mobility of certain heavy metals [219]. Microorganisms are immobilized on biochar surfaces, assisting in transforming and degrading organic contaminants [42,43].

Furthermore, Some studies have shown that biochar is effective in immobilizing a wide-ranging spectrum of contaminants, encompassing heavy metals like (Pb, Cd, and Cu) alongside organic pollutants such as aromatic hydrocarbons and pesticides [213,218]. Biochar is a promising solution for immobilizing contaminants in polluted soil and water due to its large surface area and abundant functional groups [175]. It adsorbs and binds heavy metal ions and organic pollutants, reducing their bioavailability [226,227]. Biochar also elevates soil pH, decreasing heavy metal solubility and mobility [228]. It helps immobilize microorganisms, transforming and degrading organic contaminants. Overall, biochar presents a sustainable and cost-effective approach for remediating contaminated environments [229].

Biochar application efficacy in immobilizing soil contaminants, like heavy metals, is subjected to various factors; properties of biochar, such as its source, types, surface area, pore structure, and also chemical composition, affected by the ability to adsorption of contaminants [230]. Some soil properties, including pH, organic matter content, redox potential, and microbial activity, were essential in determining contaminants, bioavailability, and the interaction between biochar and contaminants [231]. Some climatic conditions, such as moisture levels, temperature variations, and other substances in the soil, impact the stability and proficiency of biochar-contaminant interactions [232]. The application rate and method, including the quantity of biochar application rate and how it is incorporated into the soil, also impact the extent of contaminant immobilization achieved [42,43]. Furthermore, the presence and activity of soil microorganisms have impacted contaminant bioavailability and the efficiency of biochar-based remediation efforts [233]. Considering the intricate interplay of these factors underscores the importance of site-specific conditions and biochar characteristics when implementing biochar-based remediation strategies [234].

10 Biochar Application Techniques and Considerations

Biochar, an encouraging soil amendment, has several benefits when applied correctly. The first step is biochar characterization and selection, where biochar is selected based on soil and crop requirements, considering factors like stability and surface area, but due to its higher surface area and porosity contributes to improved soil properties [235]. Application methods are also involved in integrating biochar application into the soil using tillage implements for mixing, moistening the biochar before the application, and minimizing dust with mixing [236]. For perennial crops, surface application followed by incorporations is mainly preferred to avoid root damage, and appropriate application rates typically range from 5 to 50 tons per hectare [237]. Timing and their placements are also important; biochar application should be amended in the soil before planting crops and at the start of the cultivation season to permit incorporation and placing of biochar near the plant roots to take full advantage of yield production [162]. In general, selecting good quality biochar, standard application methods, and application timing are essential agronomic techniques for the most favorable soil and crop improvement [56,124]. Following these considerations are to make certain successful biochar amendments and take full advantage.

11 Challenges and Limitations

Biochar promises a soil amendment in agriculture, posing property benefits like soil remediation and upgraded crop growth by elevating soil properties like pH and water retention. However, its value varies depending on factors like manufacturing methods and soil type, with studies showing negative impacts on crop growth and greenhouse gas emissions. Challenges include predictability in high quality, costs, and monitoring uncertainties adoption. Successful incorporation and farming practices depend on agronomic and economic benefits viability. Further research and development are essential to address these issues and get the best out of biochar potential in the cultivated field.

Moreover, the long-term effects of biochar on soil health and crop productivity require thorough investigation. Field trials across diverse agricultural settings are necessary to understand its interaction with various crops and soil types. Farmers may also face barriers to adoption, such as the initial investment costs and the need for education on proper application techniques. Collaborative efforts between researchers, agricultural extension services, and farmers are essential to develop guidelines that maximize biochar's benefits while minimizing potential drawbacks. By addressing these challenges, we can unlock the full potential of biochar as a sustainable agricultural practice, ultimately leading to enhanced food security and environmental resilience.

12 Future Directions and Opportunities

Biochar has the potential as a soil amendment progressively more acknowledged by excluding GHG decline, heavy metal restriction, and improvement of soil fertility status. However, its prevalence and adoption require further research. Critical areas for future research included understanding biochar interaction with soil constituents and microbiomes. In particular, the effects on microbial and enzyme activity with biochar application should be checked. Field studies in natural environments are primarily helpful in fully comprehending biochar behavior and efficiency in soil remediation. Moreover, research should aim to produce suitable biochar types, preparation methods, timing, application rates, and reclamation processes for detailed contaminants. Inclusive environmental risk assessments and innovations in less-cost production methods are essential to promote biochar application through numerous ecological perspectives. Recent research has been subjected to various techniques to address the current issues of emerging contaminants in soil. Despite their efficiency, these methods come with several challenges. These consist of biochar's structural and physical appearance and the complexity of an amendment process associated with higher levels of pollutants.

Current methods for remediating ECs in soil face challenges, such as biochar structural limitations, complex modification techniques, and handling high pollutant concentrations. To overcome these challenges with potential strategies for improving biochar-mediated remediation and soil improvement. Biochar's ability to remediate emerging contaminants and refine production methods and properties is essential. Some factors, such as feedstock, activation methods, and pyrolysis temperature, play decisive roles in determining biochar value. Improving characteristics like porosity, surface area, and surface functional groups significantly increased its adsorption capacity. Increasing biochar properties and producing techniques by studying factors like pyrolysis temperature and feedstock type. Improving attributes such as surface functional groups and porosity boosted adsorption capacity and remediation. Biochar-based nanomaterials particularly have outstanding potential for removing contaminants.

Furthermore, innovative strategies are required to tackle high pollutant concentrations. Assimilating biochar with advanced oxidation processes. Electrochemical technologies improved pollutant degradation, converted persistent contaminants, and transferred electrons. However, these methods are not usually acknowledged in soil applications. This method offered promising solutions and innovative possibilities for improving the efficiency of biochar. To overcome the constraints of biochar-based remediation and ongoing research development are essential. This involved refining biochar properties, developing in effect on modification techniques and confronting issues linked to higher-concentration pollutants. These efforts improved the efficiency of biochar-based remediation approaches, adopting sustainable solutions used for contaminated soil remediation.

13 Conclusion

Biochar application and environmental management have prompted extensive research into farming production and socio-economic implications. Some factors influencing biochar properties, such as feedstock composition and pyrolysis conditions, are explored alongside their ability to improve soil characteristics, such as porosity and nutrient availability. Biochar can mitigate GHG emissions and immobilize heavy metals in the soil through various processes such as complex formation and ion exchange. Biochar's role in boosting agricultural farming and productivity by providing essential nutrients is notable. Regulatory standards set by our organizations, like the International Biochar Initiative, reflect the growing recognition of biochar potential. Moving forward, research efforts should focus on optimizing biochar modification for improvement of contaminant interaction and soil property improvement post-application.

The prospects of biochar in environmental management and agricultural production are promising, with a focus on optimizing biochar properties through research on feedstock composition and pyrolysis conditions. Efforts will concentrate on modifying biochar to improve contaminant interaction and soil property enhancement, such as nutrient availability and porosity, which are crucial for boosting agricultural productivity. Biochar's role in mitigating greenhouse gas emissions and immobilizing heavy metals will continue to be a significant area of study. Regulatory standards set by organizations like the International Biochar Initiative will ensure safe and effective use. At the same time, socio-economic implications, including cost-benefit analyses and farmer acceptance, will be explored to scale up biochar adoption. Integration with climate-smart agricultural practices and advancements in production technologies will further enhance biochar's benefits, making it a vital tool for sustainable agriculture and environmental remediation.

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