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Review

Biochar as an Environment-Friendly Alternative for Multiple Applications

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Abstract: The climate crisis and years of unsustainable agricultural practices have reduced soil fertility and crop yield. In addition, agricultural lands contribute more than 10% of greenhouse gases (GHGs). These concerns can be addressed by using biochar for carbon neutralization, environmental restoration, and agricultural management. Biochar has a role in nitrous oxide and methane gas emission mitigation from agricultural soil. New methods are needed to link belowground processes to functioning in multi-species and multi-cultivar agroecosystems. The intricate relationship between biochar and the composition of soil microbial communities, along with its impacts on functions within the rhizosphere, constitutes a highly perplexing and elusive subject within microbial genomics. The present review discusses how biochar can mitigate climate change, enhance carbon sequestration, and support crop productivity. Biochar could be a potential solution to mitigate soil microplastics and heavy metal contamination. Applying a biochar-based microbiome reduces polycyclic aromatic hydrocarbons (PAHs) in soil. The current knowledge and perspectives on biochar–plant–microbial interactions for sustainable agriculture and ameliorating the adverse effects of climate change are highlighted. In this review, a holistic approach was used to emphasize the utility of biochar for multiple applications with positive and negative effects and its role in promoting a functional circular economy.

Keywords: agriculture; rhizospheric bacteria; climate change; soil health

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1. Introduction

The current agroclimatic conditions are greatly perturbed by climate change, raising significant concerns. Climate change mitigation involves curbing greenhouse gas emissions and also sequestration of CO_2 [1–3]. One of the agroecosystem's biggest challenges is improving the soil fertility caused by intensive agricultural practices. In this context, biochar, a by-product resulting from the pyrolysis/gasification of waste biomass, emerges as a sustainable solution to counteract the effects of climate change [4]. Plant-based, dried biomass contains about half its weight in the form of carbon extracted and stabilized to create biochar. The ultra-porous biochar structure helps retain water and nutrients and favours the growth of microbial life in the soil. Also, biochar mitigates salt stress by enhancing the N and P availability to plants via decreasing the N leaching into the soil. Moreover, due to its inherent stability, biochar can be utilized for efficient soil and water reclamation. This approach extends to mitigating greenhouse gases, including methane (CH_4) and nitrous oxide (N_2O), concurrently enhancing soil carbon sequestration. In line with this aim, biochar has been employed to address the removal or adsorption of fluoride from naturally fluoridated groundwater or surface water. Reported methods for fluoride removal encompass electrostatic attraction, ion exchange, pore fillings, and surface complexation [5]. Similarly, biochar has been applied for managing crop residues. This strategy holds significant, yet untapped, potential to holistically tackle multiple challenges, including agricultural production enhancement, provision of safe drinking water, livelihood improvement, ensuring energy security, and strengthening environmental protection [6]. Similarly, Biochar enhances nutrient retention in soil as it provides nitrogen and phosphorus to the soil [7]. Biochar compost comprises nutrient-rich compost and biochar. Nutrient-rich compost is the product of the anaerobic degradation of organic matter. Often, biochar compost is used to replenish the nutrient deficiency of biochar.

Biochar has been acknowledged for mitigating methane emissions from paddy fields. The methane mitigation attributed to biochar primarily revolves around the modulation of methanogenic and methanotrophic populations, accompanied by alterations in their activities during methane production and consumption [8]. Nevertheless, this mechanism is subject to controversy. It is advocated that a comprehensive understanding necessitates long-term experimental investigations aimed at precisely unravelling the intricate interplay between biochar and methane mitigation within agricultural soils [9]. The prevailing notion ascribes biochar's capacity for methane mitigation primarily to its influence on methanogenic and methanotrophic dynamics, which is primarily rooted in shifts induced in soil properties such as pH, dissolved organic carbon, bulk density, and soil aeration [10]. However, an exigent requirement exists to delve into the specific attributes of biochar, encompassing its physical characteristics like porosity and surface area, as well as its chemical properties such as oxygen functional groups and electron transfer capabilities. These factors are pivotal in comprehending the extent to which they contribute to the mitigation of methane emissions.

Similarly, biochar is capable of carbon sequestration, proving valuable in climate change mitigation. It can ameliorate degraded soils, as studies indicate that its incorporation improves soil sequestration potential, augments crop productivity, and lays the groundwork for future carbon trading endeavours [11]. However, a need exists for more comprehensive research examining how distinct pyrolysis conditions impact the carbon sequestration potential of biochar [12]. Furthermore, the varying compositions of biomass feedstock and diverse agricultural waste sources significantly influence soil physicochemical attributes and biochar surface area, affecting the efficacy of carbon sequestration.

Nutrient storage in biochar and its mechanistic understanding is a relatively unexplored area. It was reported that biochar amendments in soil lead to the addition of redox-active moieties [13]. It also increases mesoporosity and hydrophobicity in the soil. These chemical changes in the soil improve the water retention capacity, thereby improving nutrient retention in the biochar-amended soil. The formation of an organic coating is associated with improved biochar efficiency [14]. The combined application of biochar and compost feedstock, known as co-composting, improves the labile carbon and nutrients with a slow release of N and P. Further, co-composting increases the agronomic performance owing to higher surface oxidation and carboxyl groups and sorption of organic molecules. Biochar coating improves its longevity in the soil by reducing its oxidative degradation, thereby protecting its aromatic surfaces. Similarly, biochar oxidation enhances the interaction between biochar and organic molecules via hydrogen bonds. Further, soil microbes play a significant role in the organic coating, which comprises mainly humic acid substances [15].

Applying biochar in combination with non-pyrogenic organic fertilizers (manures) could be an effective strategy that reduces the run-off of minerals from the soil [16]. The combined application of biochar and non-pyrogenic organic matter (manures) is an efficient strategy to reduce the application of fertilizer and its carriers. Global application of such biofertilizers could sequester more carbon and mitigate global warming. One of the major properties of biochar is its high nutrient content and slow release of fertilizers, having a higher surface area with functional moieties. Biochar incorporation effectively reduces the N_2O emission from agricultural soils [17]. For instance, an 80% reduction in N_2O emission was shown in the grass system, while a 50% decrease was shown in the soybean system. Microbial biochar formulations (MBFs) could enhance plant growth and soil fertility. Pepper plants treated with MBFs comprising biochar from microbial biowaste and *Bacillus subtilis* SL-13 resulted in superior plant and soil fertility [18]. Soil microbial communities comprising bacterial and fungal species play a significant role in the biogeochemical cycle and a range of ecosystem services [19]. Biochar application is associated with alteration in soil function and could affect carbon sequestration. Biochar application has the potential to change the soil ecology, thereby shifting the soil function. However, this shift often varies depending on the crop, climate, and specific soil. Biochar amendment increases *Proteobacteria* and decreases *Acidobacteria* abundance, often associated with higher soil nutrient content and pH [20].

Reducing the current annual emission of 50 billion tonnes of greenhouse gases by half in the next ten years and then aiming to halve it again in the following decade is required to counter the adverse effects of climate change [21]. For a very long time, residual emissions have accumulated from industrial processes, aviation, agriculture, etc. Although it is impossible to reach zero emission, net-zero emission is possible: removing as much CO_2 as we emit annually from the atmosphere. Future endeavours to restore climate balance involve removing more greenhouse gases than we emit. Biochar is no magic wand that will take us out of the climate crisis. It is part of a multipronged approach as one of the many solutions to help remove CO_2 from the atmosphere [22].

2. Biochar and Its Scaling

Biochar produced at ≥450 °C in the absence of oxygen (pyrolysis) was reported to be rich in C and more porous [23]. The thermally induced vaporization reduces the volatile matter, enhancing biochar efficacy. This biochar can be further activated for various applications following surface treatment and activation methods, including tailoring of biochar morphology, elemental composition, and functional groups. Biochar activation can be performed via (1) chemical activation, (2) physical activation, (3) surface functionalization, and (4) metal or metal oxide impregnation and heteroatom doping. Physical and chemical activation methods include carbonization via pyrolysis at 300–900 °C and biochar activation using oxidants at 500–900 °C. Oxidation of carbon at high temperatures leads to improved surface area and pore size via the evaporation of volatile matter in biochar. Though chemically activated biochar has a higher CO_2 adsorption capacity compared to physical activation, chemical activation has a higher cost of production as it requires more intensive residue removal steps than physical activation. Biomass pyrolysis, followed by activation with KOH, produces biochar with more porous C and higher efficiency [24]. Biochar efficacy can be further improved via thermal treatment under ammonia, and N_2 causes amine functionalization and nitrogen doping, respectively. Nitrogen- and ammonia-treated biochar have a higher CO_2 adsorption capacity, about threefold higher than pristine biochar and 35% higher than biochar treated with KOH. Biochar synthesized from walnut shells activated with amine functionalization, KOH, and urea treatment showed the highest CO_2 adsorption capacity, which is 7.42 mmol g^{-1} [25,26]. Furthermore, the biomass waste transformation into functional biochar material for developing supercapacitors warrants a critical evaluation [27]. This concept aligns with the growing emphasis on sustainable and innovative solutions to meet energy storage demands. Although repurposing biomass waste into functional biochar for supercapacitor development is intriguing, it demands rigorous exploration and optimization. A comprehensive analysis of the material's electrochemical properties, production consistency, compatibility, and commercial feasibility is essential before determining its potential to meet future energy storage demands [28].

3. Biochar and Climate Change Mitigation

Biochar obtained from wetlands exhibits a high sorption capacity for many organic materials and organic contaminants. Wetland-derived biochar could be employed as an efficient soil amendment owing to its abundant nutrients [29]. A recent field study reported that straw-derived biochar incorporation improves the soil water storage capacity, soil C and N, with correlative improvements in grain yield in winter wheat. Also, biochar incorporation improves the soil enzymatic activity. Thus, the strategy of employing straw-derived biochar could be a sustainable approach to improving soil fertility and crop yield [30]. The addition of biochar in the soil as a means to mitigate greenhouse gas (GHG) emissions and achieve carbon dioxide removal (CDR) was initially proposed as a global climate change strategy approximately 15 years ago. Since then, extensive research has been carried out on this concept. The biochar system significantly impacts both GHG emissions and CDR through various mechanisms: (1) decreased carbon mineralization and reduced non-CO_2 emissions arising from biochar in comparison to non-pyrolyzed biomass, (2) mitigation of emissions connected with the thermal conversion of biomass and a reduction in fossil fuel emissions if energy generation is involved (potentially coupled with carbon capture and storage, CCS), and (3) alterations in GHG emissions upon biochar addition to the soil result in enhanced plant growth, leading to additional carbon storage in plant vegetation, and diminished mineralization of soil organic matter [1]. Also, biomass pyrolysis to produce biochar is pivotal in both emission reduction and carbon dioxide (CO_2) removal. This process is not only employed for soil application but also contributes to the generation of renewable bioenergy. Biochar's efficacy in emission reduction is noteworthy, with a reduction of 3.4–6.3 $PgCO_2e$, wherein half of this reduction accounts for CO_2 removal.

3.1. Biochar as an Efficient CO_2 Sink

An increase in global surface temperature significantly contributes to greenhouse gases owing to anthropogenic activities [31]. Also, greenhouse gas (GHG) emissions from agricultural fields increase yearly. It was reported that biochar significantly reduced GHG emissions by up to 29%. Biochar-induced GHG emissions were reported to be significantly affected by the cropping systems [32]. Overall, approximately 10–15% of global warming effect is human-induced. Considering this, there is an urgent need to reduce GHG emissions from agricultural fields to prevent climate change. Previous studies advocated that biochar produced via pyrolysis could be a potential strategy to reduce global warming, considering its recalcitrant C storage in soil. Biochar can alleviate about half of CO_2 induced via human activities. Biochar affects crop yield and CO_2 emission depending on biochar properties, crops, soil types, physicochemical properties, and farm management practices (Table 1). Carbon footprint (CF) comprises carbon sources and carbon sink processes. The C source process includes pyrolysis, fertilizer, pesticide input, farm work, and greenhouse gas emissions. In contrast, the C sink process includes soil carbon increment and energy offset due to pyrolytic gas. Corn-straw-derived biochar (CBC) amendment resulted in a significant enhancement in the soil carbon pool, while there is no significant effect on N_2O and CH_4 emissions compared to the control [33]. Corn straw (CS) amendment also enhances the carbon intensity of rice production, CO_2-C equivalent (CO_2-Ce) in kg^{-1} grain compared to the control. The effect of biochar application on C reduction potential can be evaluated using CF assessment. China is the largest producer of rice and the second-largest rice-growing nation, with an area of 30 Mha. This contributes to increased GHG emissions from the paddy fields [34]. Scientists have previously promoted the use of straw application to the paddy to avoid CO_2 emission from the paddy burning. However, it has its problems, as paddy straw application causes a significant increase in CH_4 emission, thereby accelerating the global warming problem. Contrary to this, biochar (produced via straw conversion) application to agricultural soil not only enhances the soil C but also reduces the CH_4 emission from the soil, suggesting that biochar produced from the rice straw could be exploited to reduce the CF from agricultural soil [33]. Biochar is a CO_2 sportive material that is considered a promising candidate for CO_2 capture and sequestration owing to its highly porous structure [26]. Conversion of biomass C to biochar leads to 50% C sequestration compared to only 3% in burning and 10–20% in biological decomposition. Biochar could be exploited for generating fast and stable soil C, over burning or direct land biomass application [35]. Biochar has two functional amine groups that chemically interact with one of CO_2 via the zwitterion mechanism and produce ammonia and carbamate pairs as a by-product. The variations in the composition and structure of biomass feedstocks and pyrolysis parameters significantly alter the properties of biochar. The compositional matrix of biochar feedstock varied heteroatoms N, P, and S and more complex organic structures, C, H and O, and the composition of inorganic elements significantly affects the biochar efficiency [26]. Further, studying the relationship between pyrolysis conditions and resultant physical and chemical properties is necessary to design more efficient biochar with improved CO_2 adsorption. A recent study reported that P composite biochar has superior C sequestration capacity, possibly due to the stable chemical formation of C-O-P, C-PO_3, and C2-PO_2 [36]. Rice straw biochar and farmyard manure amendment mitigate the effect of herbicide bromoxynil by 78% in grain and husk, 40% in leaves, and 64% in roots in wheat. In addition, this amendment increases the wheat grain yield by 41–44% compared to the untreated control. It could be postulated that the combined treatment of biochar and field yard manure (FYM) is a potential option to reduce the herbicide concentration in plant tissues.

Table 1. Summary of biochar properties, feedstock, application, and its mechanism of action.

Feedstock	Pyrolysis	Treatment	Biochar Properties	Plants	Beneficial Traits in Plants	Reference
Cornstalk	Pyrolysis was performed at 450 °C under limited conditions.	Pot experiments were conducted with biochar mixed at the rate of 0.3, 0.6, and 1.2% with soil.	pH 8.43, EC 1.27 mS cm^{-1}, available P 106.12 mg kg^{-1}, available K 3540 mg kg^{-1}, bulk density 0.35 g cm^{-3}.	Tomato (*Solanum lycopersicum* L.) cultivar "Dongnong 708". Onion (*Allium cepa* L.) cultivar "Wangkui"	Biochar amendment significantly improved soil physicochemical properties, plant nutrient absorption, and regulated soil microbes.	[37]
Wheat straw biomass	Pyrolysis was performed in a bench-scale pyrolizer (BC350) 350 °C, (BC450) 450 °C, and (BC550) 550 °C under limited oxygen conditions. Dissolvable Organic Matter (DOM) separated from biochar.	Pot experiments were performed where soil and fertilizer were mixed thoroughly, and after 10 days, biochar extract (BE or biochar DOM) was sprayed on cabbage leaves.	BC350 pH 8.3, C 59.8%, N 7.7 g kg^{-1}, P 3.4 g kg^{-1}, K 11.3 g kg^{-1}. BC450 pH 9.1, C 62.2%, N 10.0 g kg^{-1}, P 4.5 g kg^{-1}, K 12.2 g kg^{-1} BC550 pH 9.5, C 67.4%, N 9.1 g kg^{-1}, P 5.6 g kg^{-1}, K 24.5 g kg^{-1}.	Chinese cabbage (*Brassica rapa* subsp. chinensis)	Biochar extract (BC350) significantly enhanced shoot biomass by 89%, increased sugar content by 83%, reduced nitrate by 34%, and toxic heavy metals, Cd (49%) and Pb (30%). Expression and enzyme activity of nitrate reductase and glutamine synthetase increased in treated plants.	[38]
Wheat straw	Pyrolysis was performed in a vertical kiln at a temperature of 450 °C for 2–3 h.	Biochar was applied at the rate of 20 g kg^{-1} in dry soil in pots. Biochar without chemical fertilizer (BC), biochar with chemical fertilizer (BC + CF), biochar extract and chemical fertilizers (BE + CF), biochar ash and chemical fertilizers (BA + CF), and washed biochar and chemical fertilizer (WB + CF).	Biochar pH 10.2, organic carbon 477 (g kg^{-1}), total nitrogen 5.60 (g kg^{-1}), total phosphorus 1.61 (g kg^{-1}), washed biochar pH 8.78, organic carbon 351 (g kg^{-1}), total nitrogen 3.2 (g kg^{-1}), total phosphorus 0.93 (g kg^{-1}), biochar ash pH 11.41, organic carbon 0.42 (g kg^{-1}), total nitrogen 1.1 (g kg^{-1}), total phosphorus 4.31 (g kg^{-1}).	Maize (*Zea mays* L.)	Biochar extract (BE) gave the best results, which significantly enhanced the plant biomass, total volume, and number of maize root tips.	[39]
Rapeseed straw	-	Pot experiments were conducted where biochar was applied at the rate of 40 g kg^{-1} soil for six consecutive days.	pH = 10.8, carbon content = 440 g kg^{-1}, nitrogen (N) content (total N) = 10.7 g kg^{-1}, surface area = 3.02 m^2 g^{-1}, average bore size = 2.14 nm.	Rice (*Oryza sativa* L.)	Mitigation of heat stress by improving the root zone soil organic matter, altering ratio of soil microbial community of Proteobacteria to Acidobacteria. Nitrogen assimilation, transporter proteins, root morphology, architecture, N uptake, and physiological traits were enhanced significantly.	[40]

Table 1. *Cont.*

Feedstock	Pyrolysis	Treatment	Biochar Properties	Plants	Beneficial Traits in Plants	Reference
Rice straw was dried at 105 °C for a day and milled to <2 mm before being used as a feedstock.	Pyrolysis was performed in ceramic crucibles under limited or in the absence of oxygen in a muffle furnace at 450 °C for 3 h, cooled, and sieved through a 0.25 mm sieve.	Pot experiments were conducted where rice straw biochar (RSB) was applied in conjunction with 80% nitrogen ($N_{80}B$). In another treatment, $N_{80}B$ was combined with leguminous (*Astragalus sinicus* L.) cover crop (LCC) ($N_{80}BM$).	pH 9.41, total organic carbon (TOC) 537.97 g kg^{-1}, total nitrogen 6.13 g kg^{-1}, total phosphorus 1.99 g kg^{-1}, specific area 242.24 m^2 g^{-1}, pore volume 0.14 cm^3 g^{-1}.	Rice (*Oryza sativa* L.)	Improved soil fertility, higher grain yield, straw yield, and nitrogen absorption and use efficiency in rice, reduced nitrogen pollution or N losses caused by extensive application of inorganic N fertilizers.	[41]
Maize straw	Pyrolysis was performed at 600 °C.	Biochar was applied in 10 (B10), 20 (B20), and 40 (B40) ton ha^{-1} in the field.	pH 8.14, 18.9%, C content, 0.58% N content, available K 4.76 g kg^{-1}, and available P 0.33 g kg^{-1}.	Peanut (*Arachis hypogaea* L.)	B10 significantly improved photosynthetic rate, which positively correlated with nitrogen accumulation and yield.	[42]
B1: wood chips (coniferous wood: deciduous wood = 8:2); B2: wheat straw pellets were used as a feedstock	Pyrolysis was performed at high temperature of 700 °C for 36 h.		B1 (pH 9.5), B2 (pH 10.3 ± 0.19), B1 (EC 578 µS cm^{-1} in fresh matter), B2 (1520 ± 420 µS cm^{-1}) total organic carbon B1 65.7 (wt% in fresh matter), B2 (69.04 ± 1.34 wt%). Total nitrogen B1 (0.38 wt% in fresh matter), B2 (1.32 ± 0.03 wt%). Phosphorous (P) B1 (810 mg Kg^{-1} in dry matter); 4300 (mg Kg^{-1}), B2 (2500 mg Kg^{-1})	High-yielding Italian durum wheat (*Triticum turgidum* L. subsp. durum) varieties, Duilio (V1) and Marco Aurelio (V2).	Biochar amendment increased soil carbon content, pH, CEC, and nutrient availability. Biochar induced microbial community changes. All these attributes contributed to wheat growth and enhanced crop yield.	[43]
Wood	Pyrolysis temperature 550 °C	Pot experiments were performed where seeds were sown in soil matrix having 5% biochar.	Carbon 81.1%, nitrogen 0.91%, pH value 8.21, and ash content 7.74%.	San Marzano Tomato (*Solanum lycopersicum*)	Biochar amendment induced vegetative growth and berry yield by upregulating the expression of carbon metabolism and photosynthesis.	[44]
Acacia pruning's wood	Pyrolysis at 450 °C using locally developed kiln for 4–5 h to obtain uniform size of biochar particles.	20 tons of biochar per hectare once in 50 years in agricultural fields was recommended.	pH 7.47, EC1:5 (dS m^{-1}) 1.25, available P (mg kg^{-1}) 10.9, total N (mg kg^{-1}) 9.57, total organic C (g kg^{-1}) 571.	*Triticum aestivum* L.	Improved wheat grain protein content (14.57%) and grain (62.9%).	[3,45]
Maize residue	Average pyrolysis temperature of ~450 °C.	Non-treated fresh biochar (NBC): maize residue. Washed biochar (WBC) and dissolve organic matter (DOM) biochar or biochar water-extract (BCE)	pH (H_2O) NBC (8.54), WBC (8.44), BCE (8.40); EC (ms cm^{-1}) NBC (3.34), WBC (1.79), BCE (2.34); total N (g kg^{-1}) NBC (9.39), WBC (5.78), BCE (7.83); total P (g kg^{-1}) NBC (3.32), WBC (1.69), BCE (12.19); organic carbon (%) NBC (42.94), WBC (50.28), BCE (not available).	(*Oryza sativa* L. ssp. japonica) cultivars of Wuyunjing 7 and Nipponbare	Low-molecular-weight organic acids and nanoparticles in dissolvable organic matter (DOM) biochar promoted root growth in rice seedlings.	[46]
Anaerobic pig/cattle manures and coconut husk	Coconut husk was heated at 378 °C for 70 min in an oil drum kiln under limited or absence of oxygen; thereafter, carbonization was performed.	Soil microcosm experiment was performed with and without biochar. Additionally, volatilization followed by digestate application to biochar was measured. Biochar's effect on nutrient loss was measured.	Biochar elemental composition was C (68.4%), H (3.53%), O (27.8%), N (0.06%), and S (0.15%), and pH was 9.8.	Agricultural field experiment	Enhanced soil nutrients and reduced atmospheric and groundwater pollutants, and nitrate leaching.	[47]

Table 1. *Cont.*

Feedstock	Pyrolysis	Treatment	Biochar Properties	Plants	Beneficial Traits in Plants	Reference
Wood chips and wheat straw	Pyrolysis was performed at 800 °C for 36 h using wood chips (B1) in an oxygen-free atmosphere; similarly, wheat straw was used as feedstock and pyrolyzed at 750 °C for 8 h.	1. B1—pure form. 2. B1D and B2D maize silage digestate treated.	Both B1 and B2 are alkaline pH (B1 8.5, B2 9.7). B1 had higher bulk density and lower porosity compared to B2. Electrical conductivity of B2 > B1.	Five durum wheat varieties Saragolla, Iride, Grecale, Marco, Aurelio, and Duilio	Improved plant growth traits, evapotranspiration (ET), fresh weight (FW), and dry weight (DW) in treatment with wheat straw biochar.	[48]
Straw	-	Straw mulching (SM), straw incorporation (SI), and straw-derived biochar incorporation (BI).	BI performed better compared to SM and SI in terms of plant growth and yield traits.	Winter wheat (*Triticum aestivum* L.)	Improved crop yield and soil fertility by enhancing the soil enzymatic activity and C and N.	[30]
Rice husk and corn stalk (1:1)	Slow pyrolysis at 350 °C was performed in the absence of oxygen for 3 h.	Biochar and PGPR (*Pseudomonas koreensis* and *Bacillus coagulans*).	pH 7.60, EC 0.7 dS m^{-1}, bulk density 0.2 g cm^{-3}, and specific surface area 37 m^2 g^{-1}.	Rice (*Oryza sativa* L.)	Co-application of biochar and PGPR (*Pseudomonas koreensis* and *Bacillus coagulans*) synergistically enhanced rice plant growth and productivity while alleviating water and salt stress. Enhanced nutrients, N, P, and K uptake, and superior crop productivity. Reduced proline and Na^+ content in plant.	[49]
Sewage sludge (60%) and municipal compost (40%) were subjected to pyrolysis. Biochar sieved through <0.1 mm sieve.	Pyrolysis was performed at 400 °C for half an hour.	Biochar and BM-Cotton-Plus (PGPR, *Bacillus subtilis* and *Paenibacillus azotofixans* at 1×10^7 cfu.	pH 9.3, EC 0.69 dS m^{-1}, organic matter 31.7 mg kg^{-1}, N 1.70 mg kg^{-1}, P 2.26 mg kg^{-1}.	*Triticum monococcum* L.	Combined application of biochar and PGPR had a positive effect on soil physicochemical properties, plant growth, and elemental uptake (Cu, Na, and P) of wheat. Nutrient uptake by plant was more pronounced in case of combined application of PGPR and biochar, leading to superior grain yield and growth.	[50]
Oat hulls and pine bark (PBC)	-	Oat hull biochar (OBC) and pine bark biochar (PBC).	Biochar was applied at doses of 0, 5, 10, and 20 mg per hectare in soil.	Winter wheat (*Triticum aestivum* L.)	Enhanced shoot and root biomass and grain yield in wheat. Enhanced AM spore density and mycorrhizal root colonization led to enhanced soil fertility.	[51]
-	-	Biochar and organic fertilizer	Biochar and organic fertilizers induce alteration in soil pH, NO_2 content and water-filled pore space (WFPS), which were key factors associated with change in soil microbial community shift especially denitrifiers associated with reduced N_2O emission from soil.	Wheat–maize rotation system	In wheat crop season, *Alicycliphilus* (nosZ) was the dominant genus. In maize season, decrease in abundance of *Candidatus Nitrosoarchaeum* (AOA-amoA), *Nitrosomonas* (AOB-amoA), *Mesorhizobium* (nirK), *Magnetospirillum* (nirS), and *Halomonas* (nirS) contributed to a decrease in N_2O emission.	[52]
Corn cob	Slow pyrolysis was performed at 350 °C for one hour in an electrical furnace under nitrogen flow at a rate of 0.5 L/min.	Cob corn biochar (CCB)	CBB (pH 8.1); (C% 60.30); N% (0.7); P% (2.5); (surface area 29.6 m^2/g); (water holding capacity 1.68 g/g).	Wheat (*Triticum aestivum* L.)	Biochar amendment enhanced grain yield by 13.8% challenged with salt stress, alleviating salt stress and reclaiming saline soil.	[53]

Table 1. *Cont.*

Feedstock	Pyrolysis	Treatment	Biochar Properties	Plants	Beneficial Traits in Plants	Reference
Feedstocks chicken manure (CMB), oat hull (OHB), and pine bark (PBB)	Pyrolysis was performed at 500, 300, and 600 °C, for CMB, OHB, and PBB, respectively, and maintained for 2 h.	Chicken manure biochar (CMB), oat hull biochar (OHB), and pine bark biochar (PBB)	pH (H_2O,1:5) (CMB 9.1; OHB 7.8; PBB 9.2), electrical conductivity (1:5, $\mu S\ cm^{-1}$) (CMB 924; OHB 789; PBB 724), pore diameter (nm) (CMB 3.82; OHB 3.24; PBB 3.19), total C (%) (CMB 29.67; OHB 69.02; PBB 77.5), total N (%) (CMB 2.13; OHB 1.06; PBB 0.69), P (g Kg^{-1}) (CMB 19.4; OHB 2.1; PBB 2.21), C/N ratio (%) (CMB 13.92; OHB 65.11; PBB 112.3).	*Solanum lycopersicum*	Reduced copper contamination in soil, enhanced plant biomass, and improved soil microbial enzymatic activity.	[54]
Rice straw as a feedstock for biochar (BC) and chitosan (CH)	Pyrolysis temperature was 350 °C. CH had low molecular weight and 75–85% degree of deacetylation.	Pot experiments were conducted. BC and CH were applied at 1% when applied as a sole treatment. In combination (BC and CH), half doses (0.5%) were applied.	Sunflower seeds biofortified with iron and zinc.	Decrease oxidative stress via enhanced expression of antioxidant defence system in sunflower.	Biochar can be employed to immobilize Ni in soil that reduces the concentration of Ni in seeds by up to 17%. On the contrary, phytate, Fe, and Zn concentration increase by 75%, 41%, and 42%, respectively, in seed tissue.	[55]
Rice straw husk and cow dung. Rice straw biochar (BC) and farmyard manure (FYM).	-	Two-year field experiments: different formulations of BC and FYM were applied with BC (100, 75, 50, 25, 0%) combined with FYM (0, 25, 50, 75, 100%)	-	Wheat (*Triticum aestivum* L.)	Reduced herbicide residue in grain (78%), husk, leaves (40%) and root (64%). Wheat grain yield increased by 41–44%.	[56]
Miscanthus as a feedstock for biochar.	Pyrolysis was performed in closed reactor at 350 °C.	Pot experiments were conducted with combined application of biochar (BC) and chitosan (CH)	Biochar physicochemical properties: pH 7.81, EC 1.99 dS m^{-1}, 52% organic matter (OM).	Brinjal (*Solanum melongena*)	Immobilized and reduced heavy metals; improved plant growth by maintaining homeostasis in plants. Combined application of BC and CH significantly reduced oxidative damage in brinjal plants.	[57]

3.2. Reduction of Methane Emissions Associated with Agriculture

Adding 0.5–1% biochar to cattle feed reduced methane emissions by 10–17%. Studies on cows in the US found that biochar as a feed supplement reduced cows' methane emissions by 9.5–18.4% [58]. As most greenhouse gas emissions due to cattle farming comprise methane, biochar can potentially reduce the cattle-based environmental footprint of methane emissions. Biochar reduces the methane emissions from cattle dung via the "adsorption" of methane molecules, and biochar favours the growth of certain microbes in cattle gut microbiomes that lead to more efficient digestion [9,59]. The price of biochar is a limiting factor for its use in agriculture. The recent developments in the production and use of biochar have opened up an opportunity to exploit it for climate change mitigation and the use of CO_2 certificates.

3.3. Wetlands, Biochar, and Carbon Sequestration

Wetlands play a significant role in ameliorating the adverse effects of climate change through carbon sequestration (CS) [60]. However, the positive effect of wetlands on CS potential is affected due to anthropogenic activities. Further, this decrease in CS will likely be more pronounced in the future owing to the ever-increasing global population and dynamic agroclimatic conditions. Previous studies demonstrated that wetlands play a significant role in carbon balance and mitigating climate change. In a given temporal and spatial scale, a definite amount of C sequestered in a wetland, termed carbon sequestration potential, denotes the maximum rate and amount of C stored in a wetland. A few studies reported that wetlands could store C for up to several millennia. Wetland macrophytes mainly perform CS via photosynthesis, where atmospheric CO_2 is assimilated in plant tissue in the form of sugars, which are further converted to complex lignin and cellulose in the root, stem, and leaves. Finally, after plant decay, they convert to SOC. Biochar was employed in constructed wetlands for wastewater treatment and removal of excess nitrogen from wetlands [61,62]. Wetland-plant-derived biochar plays a vital role in carbon sequestration and soil health improvement [29].

3.4. Biochar-Mediated Mitigation of N_2O Emissions

An elevated level of N_2O is one of the reasons for ozone depletion in the present environment. The source of elevated N_2O emission is the extensive use of nitrogenous chemical fertilizers in the agricultural soil, resulting in the present N_2O increase of 324 ppb [63]. Similarly, sewage-sludge-derived biochar could reduce N_2O emissions by 87%. Similarly, soil compaction, prevalent in modern agriculture, negatively affects crop yield and enhances the N_2O emission from the soil. Biochar was reported to alleviate soil compaction owing to its porous structure [64]. Also, sewage-sludge-based biochar application in nitrogen-fertilized fields has the lowest N_2O emission factor of 0.01%. A field mesocosm experiment showed that the amendment of biochar had minimal effect on wheat yield, whereas it significantly improved the vegetative growth and reduced N_2O emission from soil. It was shown that the application of biochar affects the soil's physicochemical properties like pH and nutrient mineralization, which regulates the microbial community structure, which might be associated with soil N_2O production and composition (Figure 1). Biochar amendment might enhance the abundance of ammonia-oxidizing bacteria, which cause an accelerated emission of N_2O via increased nitrification. Biochar amendments enhance the abundance of N_2O-reducing microbes, promoting denitrification [65]. Also, biochar exerts a toxic effect on denitrifying and nitrifying microbial communities, which could suppress soil N_2O emissions. Soil compaction favours the growth of denitrifying bacteria. Soil N_2O emission is primarily a microbial process where nitrifiers and denitrifiers oxidize and reduce $NH4^+$ and NO^{3-}, respectively. Similarly, soil inorganic nitrogen (N) level, moisture level, and N_2O-related microbial communities are crucial parameters for soil N_2O emission. There are two periods of N_2O emission: non-peak and peak periods. In the non-peak N_2O emission, there is competition for the available N between plants and microorganisms. Thus, substrate restriction acts as a critical factor in limiting N_2O emission. Conversely, in the peak N_2O emission period where urea is applied in the field, urea hydrolysis could provide the substrate for the nitrification, and rising levels of NO^{3-} derived from the nitrification act as the abundant substrate for the denitrification. Similarly, microplastics significantly alter the soil microbial community structure [66]. Combined application of biochar or ball-milled biochar (BM) causes a reduction in *Pseudomonadaceae* and an increase in *Methylophilaceae, Bacillaceae, Burkholderiaceae*, and *Bogoriellaceae* in amended soil. Ball milling transforms biochar into ultrafine particles. Also, ball milling leads to a threefold increase in the surface area of biochar from 85.7 to 321.9 $m^2\ g^{-1}$. Similarly, rice straw biochar was reported to decrease the N_2O emission from the nitrogen-fertilized soil. The decrease in N_2O emission is associated with a decrease in ammonia-oxidizing bacteria and ammonia monooxygenase gene (*amoA)*, *nirS*, and *nirK* copy numbers under well-watered soil conditions (Figure 2).

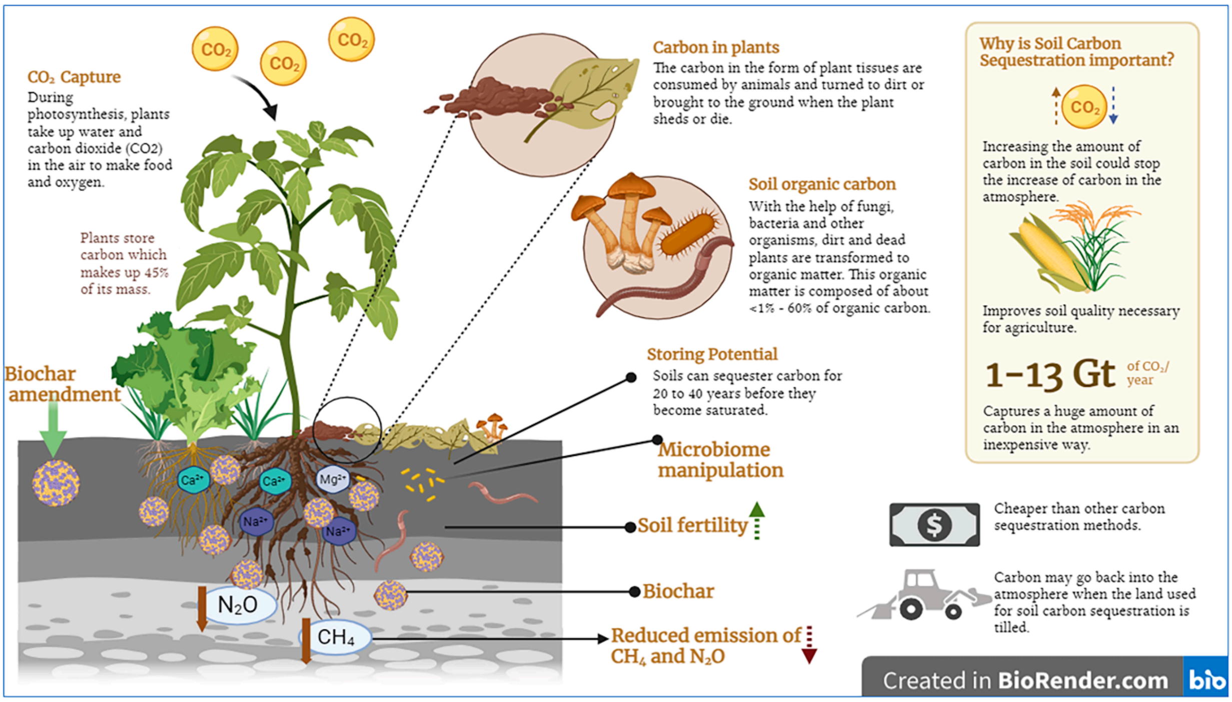

Figure 1. Processes that occur in soil amended with biochar. Biochar binds with minerals and fertilizers and helps in its solubilization, facilitating their accelerated plant uptake. Biochar significantly affects the soil's physicochemical properties. Biochar assists in carbon sequestration in the soil as it sequesters the atmospheric carbon in soil, and pyrolyzed biochar is resistant to decomposition. Atmospheric CO_2 fixed via photosynthesis is locked in the soil via biochar, resulting in accelerated C sequestration. Also, biochar is a habitat for microbes and might be associated with microbiome optimization. Biochar also reduces the emission of nitrous oxide and methane gases from agricultural soil and mitigates the microplastics from agricultural lands.

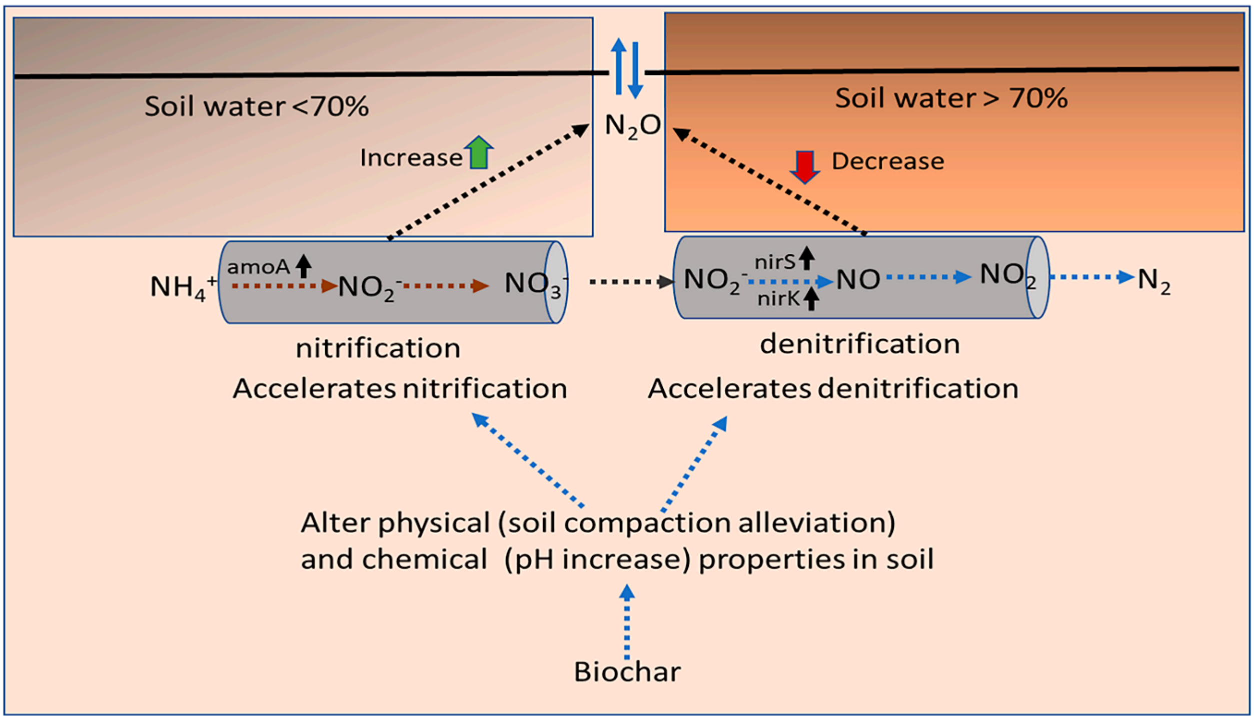

Figure 2. Biochar reduces the nitrous oxide emission from agricultural soil. Microbiological nitrogen transformation is one of the main sources of nitrogen emission from the soil. Biochar can reduce

denitrification by increasing the soil pH, thereby enhancing the expression of the *nosZ* gene. An increase in pH in response to biochar favours the growth of nitrifying and denitrifying bacteria in the soil. Additionally, they alter the relative abundance and composition of the N_2O-reducing soil microbial community. The biochar-altered microbial community promotes extracellular electron exchange or transfer to denitrifying bacteria. A decrease in the availability of NO_3^- and bioavailable C negatively affects denitrification. Biochar increased the abundance of microbial genes *amoA* and *nosZ* in alkaline soil. High moisture conditions (>70% WHC) favour nitrogen emission pathway characterized by denitrification and increased abundance of nitrate-reducing bacteria (having *nirK* and *nirS* genes) and N_2O-reducing bacteria (having *nosZ* genes), which enhance the reduction of N_2O to N_2, resulting in a net decline in nitrogen emission from the soil. (Adapted with permission from Liu et al., 2017 [66]).

4. Pollution Control, Including Adsorptive Removal and Reactive Removal of Inorganic and Organic Contaminants

Biochar-based sorbents can remove heavy metals from the soil and aqueous systems [67]. Similarly, biochar-based materials possess considerable practical potential for heavy metal bioremediation [68]. Biochar amendment in the soil can be employed to mitigate the effect of soil pollutants. Biochar acts as an adsorbent of heavy metals, facilitating the reclamation of heavy-metal-contaminated soil to ensure better plant growth. Plant–microbe-mediated remediation technology plays an indispensable role in alleviating heavy metals from the soil using biochar. Antioxidant enzymes help restrict the heavy metals in the soil as biochar amendment enhances the plant–microbe interactions that favour the colonization of the microbial community and removal of heavy metal contamination [69]. Soil-borne bacteria act synergistically to degrade polycyclic aromatic hydrocarbons (PAH) in soil. Biochar-based eco-friendly adsorbents could play an indispensable role in heavy metal ions mitigation from the soil and aquatic system. Modified biochar adsorbents (MBA) can be employed for this purpose [70]. Electrostatic adsorption is the primary mechanism responsible for heavy metal adsorption to biochar. Biochar stability and absorption ability are key to biochar's adsorption performance. Biochar application confers a significant reduction in heavy metal bioavailability in contaminated soils, resulting in lower accumulation of metals in plant tissues. Biochar interacts with heavy metals through several mechanisms such as physisorption, liming effect, cation attraction, anion attraction, ion exchange, co-precipitation, complexation, and redox reaction (Figure 3).

Biochar immobilizes heavy metals through these mechanisms. In the case of the liming effect, the biochar, which is alkaline in nature, increases the soil pH and creates more negative sites on the clay particles that attract the cationic heavy metals. Similarly, manure biochar contains more calcium, thus immobilizing the cationic heavy metals such as Cd^{2+} and Cu^{2+} through an ion exchange mechanism [71]. Also, biochar with a high amount of P can form stable precipitates and immobilize the Pb in the form of β-$Pb_9(PO_4)_6$. In contrast, higher pH and calcite in the biochar facilitate the formation of insoluble $Pb_3(CO_3)_2(OH)_2$. Similarly, biochar coated with organo-minerals can decrease the bioavailability of heavy metals. For instance, mineral-coated biochar can reduce the Cr(VI) to Cr(III) through electron shuttling and interaction with organic matter, Fe, and free radicals. All these mechanisms reduce the availability of heavy metals to plants. Biochar derived from high-temperature willow can efficiently absorb heavy metals from the sewage sludge through physisorption. The biochar derived from sewage sludge (having a high feedstock of heavy metals) can reduce the bioavailability of heavy metals/metalloids such as As, Cr, Co, Cu, Ni, and Pb and increase the accumulation of Zn and Cd in acidic paddy soil [72]. Similarly, biochar can mitigate the anionic metalloids (AsO_4^{3-}, AsO_3^{3-}) by decreasing the positively charged sites, thereby decreasing the binding sites for the As. Similarly, engineered biochar where magnetite nanoparticles were added to the biochar surface can be employed to mitigate the arsenic (As) content in the soil. Additionally, P-composite biochar was reported to suppress the *Actinobacteria* proliferation and favours the growth of

Proteobacteria, which facilitates P-solubilization and reacts with heavy metals, for instance, Pb and Cd, and immobilizes them [36].

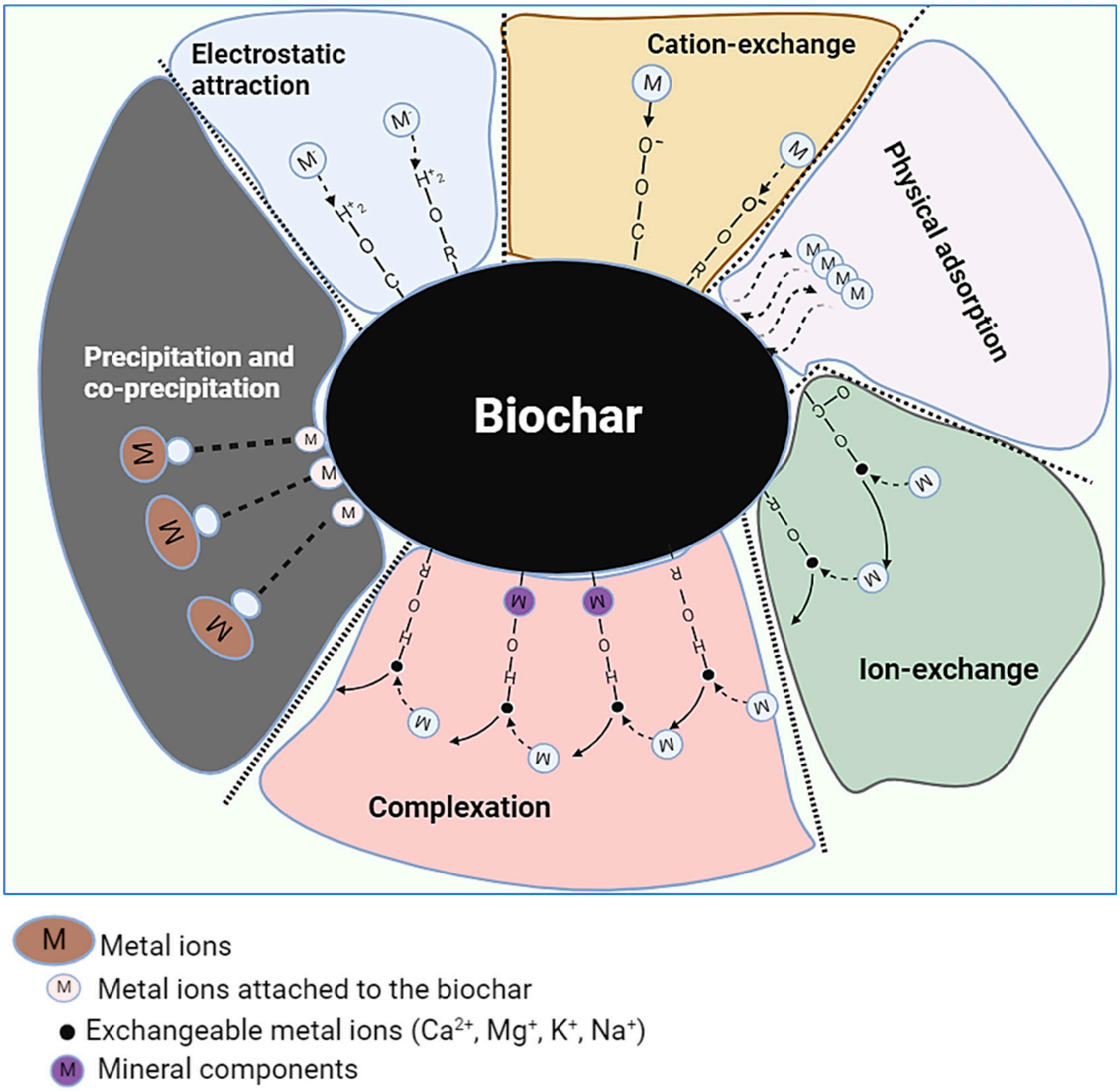

Figure 3. Various mechanisms for interactions of biochar with heavy metals and metalloids and their mitigation from soil, plants, and water.

5. Biochar Effects on Plant Growth and Health

Biochar can elicit the expression of systemic resistance and defence-related genes in plants exposed to phytopathogens [73]. Biochar can "prime" the plants for rapid upregulation of defence-related processes like oxidative burst on encountering abiotic and biotic stress. It is well known that biochar amendment significantly affects the soil/rhizosphere/pathogen/plant microbiome. To this end, the release of silicon (Si) from the biochar and absorption of pathogenic toxins by the biochar enhance disease resistance, thereby suppressing the infection caused by phytopathogens. The induced systemic acquired resistance mechanism is activated in plants grown in soil amended with biochar [74]. Biochar dose and type significantly affect plant diseases. Biochar applied at a moderate dose has a positive impact on plant disease control. However, low dose and high dose have no impact or negative impact. Considering this, biochar can induce an acclimated state to micro-stresses and primes the plants to cope with abiotic and biotic stress conditions, which might be the mechanism associated with biochar-mediated improved crop yield. At typical pyrolysis temperatures (300–700 °C), most of the N and P nutrients are retained in biochar [75]. At higher pyrolysis temperatures, 50–80% N content can be lost depending on the content of N feedstock. It was reported that sewage sludge biochar contains 6–20% of the total P content. Only a fraction of nutrients in the biochar is available in the order K > P > N for plant uptake. A previous meta-analysis reported that bioavailable N, P, and K are present in biochar in the following percentage: 0.5%, 3%, and 9% in wood-derived biochar; 5%, 5%, and 17% in manure/sewage sludge biochar; and 0.4%, 6%, and 22% in crop residue biochar, respectively [76]. Alkali pre-treatment and pyrolysis temperature influenced the silicon release from the biochar. It was shown that alkali pre-treatment and pyrolysis temperature (at 550 °C) enhance the Si release from the biochar and could be an environment-friendly approach to protect the plants from phytopathogens. For instance, the rice-straw- and rice-husk-derived biochar pre-treated with KOH, CaO, and K_2CO_3 and pyrolyzed at 350, 450, and 550 °C causes a higher release of Si from the biochar [77]. Alkali-enhanced and Si-enriched biochar can confer tolerance to plants from biotic stresses. A greenhouse study showed that rice plants performed better in terms of Si uptake and crop yield treated with alkali-enhanced biochar. Biochar amendments, buffer pH, and oxidation/reduction potential (Eh) maintain the rhizosphere condition to support plant growth and cope with dynamic agroclimatic stress conditions. Biochar can rapidly transfer the charges associated with cellular homeostasis conditions and cope with oxidative stresses. In summary, biochar favours the rhizosphere conditions that improve nutrient supply and uptake, mitigates the uptake of phytotoxic organic and mineral substances, enhances bioactive metabolites associated with improved plant growth and development, and promotes the growth of beneficial microbes while inhibiting the growth of phytopathogens.

5.1. Improved Nutrient Supply for Crops and Higher Yields

A meta-analysis on the effects of biochar on the P availability in agricultural soils reported that adding biochar increased the P availability by a factor of 4.6 [78]. It also decreased the concentration of heavy metals in plant tissues by 17% to 39%. It enhanced the build-up of soil organic carbon by 3.8% and reduced the non-CO_2 greenhouse gas emission from the soil by 12–50%. All these beneficial effects resulted due to the addition of biochar increasing crop yield by 10–42%. Using appropriate and site-specific biochar mitigates the soil constraints, water limitations, and nutrient availability, resulting in higher crop yields. Most of the biochar amendments are alkaline and neutralize the acidity of the lime agricultural soil by up to 33%, owing to oxide, carbonate, and hydroxide attributes.

Biochar can increase or decrease the nutrient concentration in plant tissues. Biochar based on poultry litter (PL), swine solids (SS), and blends of poultry litter and pine chips (PC) decreased the Ca, Mg, and Zn concentration in lettuce leaves [79]. Similarly, in the case of carrot root, nutrient concentrations decreased. However, the decrease was not as prominent as it was in the case of lettuce root. In contrast, biochar based on PL and PC/PL, 50%/50%, increased the K concentration in carrot taproot. Biochar combined with *Burkholderia phytofirmans* PsJN enhanced grain Fe concentration, crop productivity, and soil fertility. Siderophore-producing bacteria (PsJN), in combination with organic amendments, improve the iron concentrations in grain tissues of *Chenopodium quinoa*, especially under acidic soil conditions. Similarly, the combined application of Zn and biochar gave superior crop yield and grain Zn concertation [80]. Biochar acts as a resistor–capacitor circuit (RC circuit) in the rhizosphere, regulating the controlled release of organic/inorganic nutrients and electrons.

5.2. Nutrient Loss Reduction

Biochar can act as a switch to store and release the inorganic and organic nutrients and ions whenever the plant needs them [81]. Biochar made at a temperature > 400 °C has a higher content of free radicals, which causes the release of high levels of reactive oxygen species, thereby accelerating oxidation not only in biochar itself but on soil organic matter (SOM) and plant residues, especially in soil prone to intensive agricultural practices, or in soil with a very dynamic water level and iron oxides. When water enters biochar pores, it enhances the dissolution of organic and mineral compounds, thereby increasing the dissolved organic carbon (DOC), cations, and anions in the soil solution. These dynamic fluctuations in the ions positively affect the soil pH and electrical conductivity. The extent of change in soil physicochemical properties depends on the application of specific biochar and soil properties. At the initial phase, rapid dissolution of salts, ion exchange, particle detachment (submicrometre), and preferential dissolution occur. As the rapid dissolution process ends, the continued dissolution begins mainly in acidic soil conditions and nutrient-deprived soils. When biochar is applied in combination with minerals such as N and P, it causes the slow release of N compounds in the soil compared to inorganic chemical fertilizers. To this end, the slow release of N compounds in the soil could be attributed to the changes in physical and chemical reactions. Biochar-based slow release of fertilizers is a viable option for promoting sustainable agriculture [82].

5.3. Activity of Biochar on Different Soil Types

Although biochar is an excellent amendment for soils with different textures, its activity varies with soil types. Green coconut residues and sugarcane bagasse biochars showed the highest water-holding capacity (62%) in the tropical soil, Typic-Quartzipsamment, compared to Ultisol and Luvisol [83]. The sugarcane bagasse biochar increased the plant available water in the Typic-Quartzipsamment by 40%. Biochar reduced the bulk density of most soil types, improving physical and biochemical properties and microbial activity. Biochar improved the water-holding capacity of the coarse-textured soils, whereas it improved soil porosity and water transmission of the clayey soil. Overall, using biochar in sandy and medium-texture soils resulted in superior performance than in clay soil.

Further, the smallest particle size biochar of date palm showed the best effect on water content and soil structure of sandy loam soil, requiring less water for irrigation [84]. The straw- or grass-derived biochar increased the water-holding capacity [85]. After more than one year of production, the ageing biochar enhanced the water-holding capacity (WHC).

5.4. Slow-Release Fertilizers (SRF)

Leaching of the chemical fertilizers in the soil is a major reason for environmental pollution, creates a huge challenge for global sustainability, and causes significant financial loss. In addition, extensive application of chemical fertilizers has a negative effect on farming lands due to soil salinization and depletion of organic matter. To address the drawbacks of conventional chemical fertilizers, the application of slow-release fertilizers (SRF) has gained significant global attention [86,87]. There are several advantages of SRF, such as a low release rate of nutrients, thereby having prolonged availability of nutrients for plant uptake and decreasing the nutrient loss in agricultural soil.

The potential application of biochar-based fertilizers is still in its infancy. The loading of nutrients onto biochar can improve its efficacy as a fertilizer. To this end, pristine biochar having limited nutrients when applied with N and P nutrients improved crop productivity [87]. Several reports advocate the efficacy of biochar-based slow-release fertilizer (SRF) [58,88–90]. Biochar has several properties that make it suitable for sustainable agriculture, such as high carbon content, optimal pH, cation exchange capacity, and high surface area. Biochar derived from corn cob and applied as a nano-composite enhanced the uptake of macro and micronutrients by plants acting as SRF, which enhanced WHC, water absorbance and swelling ratio, and equilibrium water content [91]. Overall, these SRFs increase fertilizer effectiveness through reduced nutrient loss and leaching.

6. Biochar Significantly Alters the Soil Microbiome

Biochar has a significant effect on bacterial and fungal soil microbial communities. However, these changes are less than the highly variable soil microbiome occurring in different soil types and changing with time. 16S rRNA and ITS short-read amplicon sequencing revealed changes in microbial diversity with an increase in *Acidobacteria* and

Actinobacteria, which was associated with carbon molecule decomposition and carbon cycling [92,93]. Further, biochar application decreased the abundance of bacteria belonging to several genera [94].

The soil microbial dynamics may be attributed to differences in biochar quality and environment. A recent study highlighted the indispensable role of mycelia and hyphosphere processes in soil organic carbon sequestration under enriched-nitrogen conditions in alpine forests [95]. Negative plant–soil feedback (NPSF) significantly affects sustainable agricultural ecosystem development strategies. Biochar application could alleviate the NPSF as they modify the soil microbiome. Biochar application significantly affects bacterial and fungal diversity, affecting soil pH, organic matter, available P and K, electrical conductivity, and C/N ratio. There is a strong correlation between soil chemical variables and microbial community diversity. Biochar amendment is associated with the recruitment of beneficial bacteria, *Bacillus* and *Lysobacter*, which suppress the phytopathogens *Ilyonectria* and *Fusarium*. These studies suggest that biochar application has no direct effect on suppressing the growth of *Fusarium solani*, but they recruit the biocontrol bacterium *Bacillus subtilis* [77].

The microorganisms colonize biochar, forming biofilm at its surface [96]. From the material point of view, soil topology, surface roughness and free energy, hydrophobicity, and surface charge are the main parameters during the attachment of microorganisms. Microbial biofilm formation was reported to be faster on non-polar hydrophobic surfaces than on hydrophilic ones. The major factors associated with biofilm development include the roughness of soil surfaces and competition between protozoa and bacteria.

Biochar is porous and can be a habitat for fungi and bacteria. There are few reports where beneficial microbes were immobilized on the biochar surfaces. These treatments were applied in corn with *Pseudomonas putida*, soybean with *Bradyrhizobium japonicum* [97], and cucumber with *Enterobacter cloacae* [98]. The functional groups on the biochar surfaces serve as sites for microorganism colonization and elicit specific reactions, facilitating biofilm formation on biochar surfaces. Similarly, soil microbes utilize low-molecular-weight hydrocarbons as a carbon source. They also act as signalling molecules that inhibit and stimulate plant growth and microbial activity. Biochar binds and interacts with organic and non-polar molecules, which might be associated with intercellular communication. Hence, it was proposed that biochar can elicit gene expression dependent on intercellular signalling. These molecular underpinnings could be employed in future biochar preparation for the optimization of soil microbial-dependent processes as a measure to control the phytopathogen attack and nitrogen fixation in crops [99].

7. Interactions of Biochar, Microplastics (MPs), and Soil Microbiota

Plastic mulch is extensively used in agriculture for plant growth, crop yield improvement, soil water retention, minimizing weeds' growth, and controlling the soil temperature. Low-density polyethylene (LDPE) is a commonly used mulch that releases macro- and microplastic (MP) residues in agricultural fields. LDPE in the soil is reported to decrease plant growth and crop yield as it significantly alters the rhizosphere microbial community and soil physicochemical properties and decreases the water retention capacity of the soil [100]. Biochar amendments can improve the overall quality of soils contaminated with MPs. However, its effectiveness depends on pyrolysis and temperature conditions, suggesting that it is important to identify the suitable biochar associated with the mitigation of the microplastics from the contaminated soil. It was reported that MPs in soil negatively affect the soil biodiversity and overall soil microbial community. Biochar amendments alter the soil pH, available phosphorus, total exchangeable cations (TEC), and electrical conductivity, improving soil quality. It was reported that a hybrid biochar sand filter is promising as a low-cost system for microplastic removal [101]. Oilseed rape straw (OSR)-derived biochar amendments in the MP-contaminated soil significantly affect soil enzymatic activity, such as an increase in the fluorescein diacetate activity and a decrease in acid phosphatase activity. Biochar supplementation resulted in a higher abundance of bacteria belonging to the phyla *Firmicutes*, *Proteobacteria*, *Actinobacteria*, *Dictyoglomi*, and *Gemmatimonadetes*. The choice of suitable biochar to improve the soil quality of MPs contaminated soil depends on the pyrolysis feedstock and temperature. MPs contamination causes modification of microbial community, thereby affecting the soil ecosystem's carbon cycling and overall function. MPs in the soil not only alter the soil microbiome but also alter the biogeochemical cycles. Some genera like *Pedomicrobium*, *Mycobacterium*, and *Hyphomicrobium* were shown to tolerate MPs as they can grow in the presence of a high concentration (7%) of low-density polyethylene (LDPE). LDPE upregulated the expression of various genes associated with nitrogen cycling, such as *nirK*, *AOBamoA*, and *nifH*.

Similarly, combined application of ball-milled biochar and polyethylene plastic fragments (PEPFs) and degradable plastic fragments (DPFs) were reported to enhance polycyclic aromatic hydrocarbon (PAH) and phthalate ester (PAE) removal from contaminated soil with the help of microbial community members belonging to genus *Nevskia*, *Ralstonia*, *Gemmatimonas,* and *Lysobacter*. Similarly, the higher abundance of the pyrene dioxygenase gene (nidA) in soil was positively associated with pyrene removal [102]. The mitigation of organic pollutants might be due to the high absorption rate of biochar and PEPF and the increased abundance of PAE or PAH degraders. A recent study demonstrated that steam activates spruce-bark- and Scots-pine-derived biochar, which performs better in mitigating the residual organics, cations, and microplastics from the wastewater and aqueous media owing to their higher porosity and adsorbents attributes [103]. The steam-activated biochar was reported to be a low-cost, high-performing biobased strategy for purifying industrial wastewater and microplastic removal. The sorption mechanism of macro- and microplastics in biochar remains elusive. However, the porosity in biochar may facilitate the macro-, micro-, and nano-plastic retention in biochar [104]. The retention mechanism is supported by the better performance of spruce-bark-derived biochar, which has a relatively low surface area and high porosity. The possible physical attachment between microplastics and biochar particles could explain the retention mechanism. Superior biochar retention capability may be due to the biochar surface roughness. These studies suggest a need to understand better the mechanisms of MP retention by the biochar surfaces. Biochar represents an inexpensive and eco-friendly approach to mitigate the MP contamination from the soil and aqueous system. In addition, the economic feasibility of biochar production and retention mechanism should be considered in future research.

8. Biochar and Circular Economy

Biochar has excellent potential to mitigate the negative impact of climate change and pave the way for a circular economy model. Transforming the waste to biochar is a sustainable way to a circular economy. International guidelines should be proposed for biochar use, especially for the toxic heavy metals and their environment-friendly applications [105]. Pyrolysis retains a large portion of nutrients in the biochar, while incineration destroys most of the organic nutrients. Pyrolysis retains around 50% of the feedstock C, contrary to incineration. In addition, the gases produced by pyrolysis can be utilized as renewable energy sources. Biochar can be used instead of peat, reducing N losses, speeding up composting, and generating higher-quality compost [106]. The various attributes of biochar that contribute to an efficient circular economy include serving as a habitat for beneficial microorganisms, increasing aeration, gas exchange and WHC, inhibition of toxins and desiccation, and retention of nutrients. Biochar can be optimized to absorb more nutrients from wastewater; hence, amended soil can be loaded with more nutrients available for plant growth, thereby reducing the concentration of N and P in wastewater and preventing eutrophication.

9. Limitations of Biochar

Although the application of biochar can benefit soil health and remediation, production of biofuels, mitigate waste disposal problems, and mitigate climate change through carbon sequestration, there are trade-offs where maximization of mitigation of climate change and enhancement of soil fertility leading to higher crop productivity reduced the benefit for biofuels [107]. Similarly, the use of waste products used to make biochar compromise, to some extent, their maximum utility for soil fertility. The utility of biochar to enhance crop productivity depends on the environment and soil type, with an average increase of ~25% yield in acidic soils in tropical regions and no significant increase in temperate regions [108]. Despite the numerous benefits of biochar shown by researchers, the use of biochar by farmers is limited due to various reasons, including ground-level realities, the financial benefit to farmers, and translational research issues [109].

10. Biochar Production and Factors to Be Considered for Its Applications

The utilization of forests for biochar production could potentially lead to substantial CO_2 emissions, particularly if the utilized forests are not replenished. Therefore, the application of forests for biochar production should be restricted to the realm of sustainably managed forests [1]. Conversely, the use of purpose-grown biomass crops for biochar production, with subsequent regrowth, allows for the gradual rebuilding of carbon stores over successive cycles. In a similar vein, biomass feedstock, when left to decompose without pyrolysis, releases CO_2 at a notably slower rate compared to thermal conversion processes. Crop residues decompose over annual timescales, incurring a minor carbon debt that is outweighed by the significant increase in carbon achieved through pyrolysis [110]. The potential of employing nutrient-rich wastes, like excreta, for biochar production and subsequent recycling holds unexplored promise in emission reduction through their role as biochar feedstocks [111]. Despite the burgeoning academic interest in various biochar applications, its widespread adoption remains limited due to economic impracticality when juxtaposed with conventional fertilizers. Farms often need more awareness or exhibit scepticism about their impact on agricultural systems.

In light of these challenges, it is recommended to undertake thorough cost–benefit analyses of biochar production and application, gauging its profitability from both an investor's standpoint and its societal desirability. The profitability and attractiveness of biochar production and application remain uncertain, significantly influenced by factors such as feedstock, scale, pyrolysis conditions, biochar pricing, and the response of cultivated crops. This complexity poses a barrier to large-scale private investments in biochar production. To advance biochar production and deployment, careful consideration of these conditions is imperative [112,113]. To navigate these complexities, collaborative efforts between scientists and environmentalists and a comprehensive evaluation of the economic costs of biochar production focusing on both costs and benefits are required.

11. Pros and Cons of Biochar

Biochar and its derivatives have a pivotal role in mitigating greenhouse gas emissions like CO_2, N_2O, and CH_4 originating from soil and organic fertilizers, which is supported by findings from field studies [114]. However, it is essential to acknowledge that the effectiveness of biochar in curbing greenhouse gas emissions is contingent upon controlled environmental conditions. Large-scale investigations have unveiled a nuanced perspective, where the impact of biochar either remains neutral or, in some cases, leads to an adverse effect on greenhouse gas reduction. Furthermore, the efficiency of biochar's role in emission reduction is intricately tied to multiple factors. These include the proportion of biochar application, the pyrolysis temperature during its production, and the specific type of feedstock utilized for its creation. Biochars derived from organic sources and pyrolyzed within the temperature range of 500 to 600 °C, when applied conservatively at rates below 10 Mg ha^{-1}, demonstrate heightened efficacy in minimizing greenhouse gas emissions while promoting carbon sequestration. The composting of sewage sludge has been linked to various ecological concerns. However, a positive development in this area indicates that incorporating rice straw biochar at levels ranging from 8% to 18% during sewage sludge treatment effectively mitigated greenhouse gas emissions [115]. Furthermore, a similar beneficial effect was observed when bamboo biochar was introduced into sewage sludge, resulting in substantial reductions in CH_4 and N_2O emissions by 45.7% and 3.7%, respectively. The Intergovernmental Panel on Climate Change (IPCC) acknowledged biochar as a technology for negative emissions [116]. However, the use of biochar to enhance crop productivity showed mixed results, with ~50% of the studies conducted indicating that the addition of biochar leads to enhanced crop productivity, while the remaining 50% revealed no statistically significant differences. Earlier findings indicated that the addition of biochar improved soil nutrient levels, enhanced water retention capabilities, and led to a decrease in N_2O emissions. However, these positive effects were counterbalanced by a significant reduction in yield performance, as shown in the banana. Intriguingly, there was no observable impact on papaya yield. This serves as a reminder that a biochar-based organic amendment might not consistently yield favourable outcomes in the context of tropical agriculture [117]. Similarly, specific investigations revealed that the incorporation of mango wood biochar contributed to heightened soil phosphorus availability. However, this improvement came at the cost of a negative influence on arbuscular mycorrhizal fungi (AMF) abundance in the soil [118].

The interplay between biochar and potentially toxic elements hinges on various biochar properties such as surface functional groups, mineral content, ionic composition, and π-electrons. These attributes collectively determine how biochar impacts the (im)mobilization of potentially toxic elements (PTEs), resulting in complex and highly element-specific dynamics. Interestingly, the converse effect of the interaction between biochar and PTE mobilization can be strategically utilized. Biochar's potential as a mobilizing agent can be harnessed to enhance phytoremediation efforts for heavy-metal-contaminated soils, particularly PTEs [119].

12. Conclusions

Biochar is comparatively inert and resistant to microbial and chemical degradation and holds great potential to contribute to waste, energy, and pollution management. Biochar application can reduce the emission of methane and nitrous oxide emission from agricultural lands. Biochar has immense potential to increase crop yield, especially in nutrient-deficient soil, high phosphate-enriched acidic soils and sandy soils, and tropic and subtropic agricultural soils that are more likely to be affected by the increasing drought and changing agroclimatic conditions. Another important application of biochar is the immobilization of heavy metals, thereby reducing plant uptake and availability in soil. Biochar's heavy metal mitigation property significantly impacts food production and its safety as it could reduce the contamination of toxic heavy metals in the food chain, especially in developing countries like India. Furthermore, we advocate for using biochar derived from waste materials to promote the principles of a circular economy, aligning with sustainable resource management practices.

There is a need to quantify biochar's enduring impact and potential contamination risks on both soil and vegetation. This underscores the urgency for comprehensive research delving into factors such as plant growth responses, effective utilization of biomass, and the release of CH_4 and N_2O from the soil. Additionally, the refinement of biochar systems should encompass strategic considerations like optimizing biomass sourcing and implementing adequate vegetation cover, all aimed at maximizing carbon sequestration potential. To augment the adoption of biochar applications, it is crucial to heighten awareness through government initiatives and incentives within the market. By integrating education and emphasizing the correlation between biochar use and amplified crop yields, there lies an opportunity to augment farmers' earnings. Furthermore, we advocate for a thorough assessment of biochar, encompassing its environmental ramifications and broader societal implications, extending beyond climate change mitigation.

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