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Review article

Biochar as a sustainable soil amendment: Impacts on soil properties, plant growth, and agricultural productivity

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ABSTRACT

The limited availability of land and the global demand for sustainable food production have driven interest in soil amendments that raise crop yield without compromising ecological balance, alongside the continued use of organic and inorganic fertilizers. Excessive and unregulated chemical fertilizer use has instead contributed to declining soil fertility, biodiversity loss and increased greenhouse gas emissions. Biochar, a porous, carbon-rich product of biomass pyrolysis, has emerged as a soil amendment capable of addressing several of these challenges simultaneously: it improves nutrient retention through its high cation-exchange capacity and surface area, supports plant growth-promoting microbial communities by providing a protective colonization substrate and contributes to soil carbon sequestration. This review synthesizes evidence from 320 peer-reviewed studies (2015–2025), identified through a systematic multi-database search, on the mechanisms by which biochar alleviates abiotic stress, supports seed germination and seedling vigour and enhances plant growth and yield through synergistic interactions with plant growth-promoting rhizobacteria and mycorrhizal fungi. Despite consistent evidence of agronomic benefit, large-scale adoption remains limited by variability in feedstock characteristics, pyrolysis conditions, application rates and site-specific soil-climate interactions, as well as by production costs and a scarcity of long-term field trials. This review critically examines these constraints and identifies three priority research directions: standardized, multi-year field trials across soil types; mechanistic studies of biochar-microbe interactions under field conditions and economic assessment of biochar-biofertilizer co-application at farm scale.

1. Introduction

The worldwide demand for food, diminishing arable area and growing dependence on organic and artificial fertilizers have heightened stress on agricultural soils. Continuous farming exhausts soil nutrients and this depletion, together with erosion and overuse of chemicals, has led to reduced yields in numerous agricultural systems [1]. Climate change and salinity, aggravated by inadequate irrigation methods and increasing groundwater levels, impact over 20% of the world's irrigated lands, decreasing crop productivity [2]. Fertilizers are essential for restoring nutrients depleted by continuous farming [3], although their overapplication deteriorates soil health, negatively impacts biodiversity and leads to pollution, hence increasing the need for more sustainable, slow-release options [4]. Biochar has surfaced as a potential option, even though its function requires clean articulation. In its original state, biochar possesses minimal nutrient composition and does not function as a fertilizer; its worth is derived from its formulation and integration with additional nutrient sources [5]. Biochar-based fertilizers (BBFs), biochar that has been co-composted, coated, or impregnated with nutrients, are one such formulation, and have shown improved crop yields, reduced nutrient loss, and greater nutrient-use efficiency compared with unmodified biochar [6]. In soils that respond poorly to conventional fertilizers, BBFs have been reported to increase yields by roughly 10–15% relative to standard fertilization [7,8].

Biochar itself is a carbon-rich material composed largely of cellulose- and lignin-derived structures, produced by pyrolysis of biomass under low-oxygen conditions. Pyrolysis proceeds through drying, thermal decomposition, and cooling stages, and both the temperature and duration of the process determine the resulting biochar's properties: higher pyrolysis temperatures generally yield more stable, carbon-dense

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biochar. Feedstock choice- manure, food waste, wood waste, or crop residues- further shapes the final product's composition and functionality [9]. These production variables translate into the physicochemical properties that make biochar agronomically useful: high porosity, large surface area, and strong nutrient-retention capacity. Together, these properties improve soil fertility and water-holding capacity, support beneficial soil-microbe interactions, and help soils resist abiotic stress, effects documented across acidic, sandy, and contaminated soil types [10] Biochar's surface functional groups also allow it to adsorb and slowly release nutrients, reducing leaching losses, and to act as a carrier for plant growth-promoting bacteria, improving microbial survival and colonization in the rhizosphere. Because biochar interacts with soil nitrogen species (e.g., NH_4^+ and NO_3^-), it can influence nitrification and denitrification dynamics, though the exact mechanisms depend on biochar type and soil conditions [11]

These agronomic effects have downstream implications for soil health and climate. Biochar application has been associated with improved soil chemical and physical properties, including greater bioavailability and plant uptake of nitrogen, potassium, and phosphorus [12], and with support for nitrifying and denitrifying microbial populations that enhance nitrogen-use efficiency and crop productivity [13]. Under appropriate production and application conditions, biochar has also been linked to reductions in soil greenhouse gas emissions, offering a potential co-benefit for climate mitigation alongside its agronomic role [14,15]. Biochar's effect on soil greenhouse gas emissions is not uniformly positive: sugarcane bagasse biochar has been shown to reduce N_2O emissions in rice paddy systems, though this benefit can be offset when biochar is co-present with polystyrene microplastic contamination, which independently increases N_2O output [16]. Similarly, while biochar is often cited for climate mitigation potential, at least one paddy soil study found biochar application increased CO_2 emissions relative to untreated soil, with the effect compounding in the presence of microplastics [17]. These findings indicate that biochar's net GHG effect is contaminant- and context-dependent rather than a fixed benefit. Other agronomic strategies — such as water management combined with wheat straw addition [18], or optimized manure and irrigation coordination [19] offer complementary or alternative routes to methane mitigation in rice systems.

Biochar's utility is not limited to soil amendment; it has also been explored for pollutant remediation relevant to agricultural systems, including removal of per- and polyfluoroalkyl substances (PFASs) through mechanisms such as hydrophobic interaction, electrostatic attraction, pore filling, and hydrogen bonding [20–22]. Modified forms, including composite and magnetically functionalized biochar, have shown efficacy in removing heavy metals such as hexavalent chromium from soil and water while limiting secondary pollution [23]. Biochar-supported microbial communities can further immobilize contaminants and improve soil structure, reducing the risk of pollutants entering the food chain [24]. Beyond PFAS and heavy metal remediation, biochar has also shown potential in mitigating total petroleum hydrocarbon (TPH) contamination, with biochar-amended rice showing improved growth, yield, and biomass compared to TPH-only treatments [25]. More specialized applications, such as algal biochar for microplastic removal, illustrate the breadth of ongoing research, though these fall at the periphery of this review's agricultural focus and are noted here only for context [26]Taken together, this body of work positions biochar and BBFs in particular as a promising, evidence-supported tool for improving soil properties and agricultural productivity, while highlighting that its effectiveness depends strongly on feedstock, production conditions, and formulation. The remainder of this review examines these factors in detail, focusing on biochar's impacts on soil properties, plant growth, and productivity in agricultural systems

2. Review methodology

This review adopts a structured narrative review approach to synthesize current knowledge on biochar as a soil amendment and plant growth promoter. While not a formal systematic review with a pre-registered protocol, the literature search and screening process followed a transparent, reproducible, multi-stage procedure, detailed below.

2.1. Search strategy

Literature was retrieved from four databases — ScienceDirect, SpringerLink, PubMed, and Google Scholar — selected to provide broad coverage across soil science, agronomy, microbiology, and environmental engineering. Web of Science and Scopus were not directly queried; where indexing overlap exists, relevant records from these databases were captured indirectly through Google Scholar's aggregated indexing, though we acknowledge this is not equivalent to direct querying and may have excluded some indexed records unique to those platforms.

Searches were conducted using Boolean combinations of the following terms “("biochar" AND ("plant growth" OR "plant growth-promoting rhizobacteria" OR "PGPR")), ("biochar" AND "soil fertility"), ("biochar" AND "soil amendment"), ("biochar" AND "microbial communities"), ("biochar" AND "crop productivity"), ("biochar" AND ("salinity stress" OR "drought stress" OR "heavy metal stress")), ("biochar" AND ("fertilizer" OR "compost" OR "microbial inoculant")). Searches were restricted to publications dated January 2015–February 2026, and to English-language, peer-reviewed journal articles with available full text.

2.2. Study selection

The over all PRISMA-style flow diagram of the literature identification, screening and inclusion process is illustrated in Fig. 1.

Inclusion criteria: Peer-reviewed English-language journal articles (2015–2026) with full-text access, focusing on biochar production/characterization and its effects on soil health, plant growth, microbial activity, or crop productivity; studies on biochar-mediated abiotic stress tolerance (salinity, drought, heavy metals); and studies on biochar combined with fertilizers, compost, or microbial inoculants.

Exclusion criteria: Non-English publications, articles without full-text access, conference abstracts/preprints/non-peer-reviewed reports, and studies not directly addressing biochar's agricultural or soil applications.

Screening process: The initial search returned 658 records. After removal of 120 duplicates, 538 records underwent title/abstract screening. Of these, 140 records were excluded as off-topic, non-peer-reviewed, or lacking full-text access, leaving 398 records for full-text assessment. Full-text screening against the inclusion/exclusion criteria excluded a further 78 records, yielding a final set of “x” studies included in the review

Quality appraisal: Given the heterogeneity of study types (lab, greenhouse, field, meta-analyses), formal clinical risk-of-bias tools were not applied; instead, studies were screened for methodological transparency (replication, statistical reporting, disclosed experimental conditions), and those lacking these elements were excluded at the full-text stage.

Data extraction and synthesis: For each included study, we extracted biochar feedstock/pyrolysis conditions, soil or crop system, experimental design, key outcomes (yield, nutrient availability, microbial abundance), and reported mechanisms. Data were organized thematically by the review's major sections. Given heterogeneity in experimental conditions and outcome measures across studies, synthesis was qualitative and narrative rather than a pooled meta-analysis; comparable quantitative findings (e.g., yield changes) are presented descriptively rather than statistically combined.

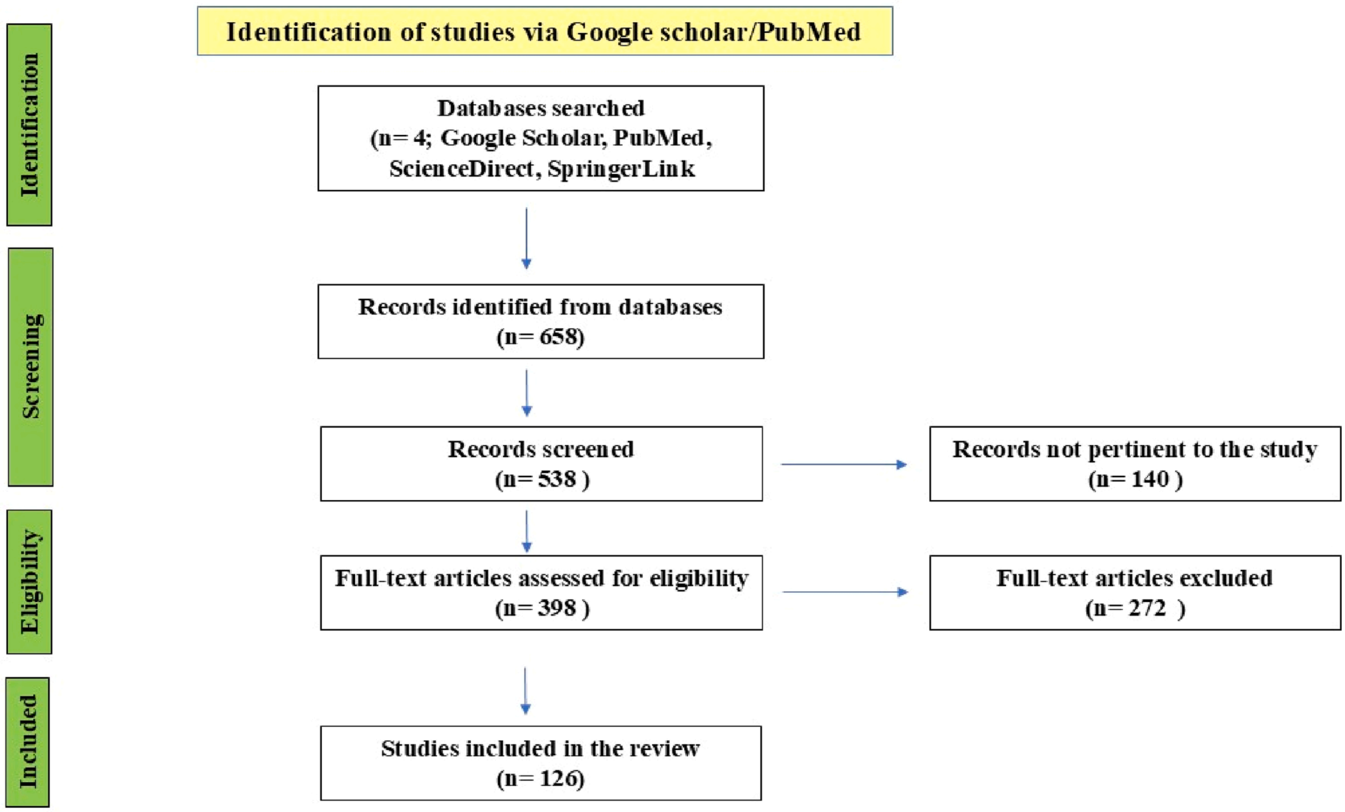

Fig. 1. PRISMA-style flow diagram of the literature identification, screening and inclusion process. Records were identified from four databases (Google Scholar, PubMed, ScienceDirect and SpringerLink; n-658). Following title /abstract screening, 140 records were excluded as not pertinent to the study, leaving 398 full-text articles assessed for eligibility. Of these, 272 were excluded at the full-text stage, resulting in a final set of 126 studies included in the review.

3. Mechanisms of biochar action on plant growth

Biochar improves plant growth through multifactorial processes, including major techniques such as topsoil integration, subsurface application, and surface dressing [26]. The absorption of nourishment by plants depends on the nature of biochar, which modifies the chemical makeup of soil, affecting factors such as pH and the amount of organic carbon present. Biochar action involves the incorporation of various minerals and microorganisms into soil. The functional groups in biochar improve nutrient absorption and increase the stability of vegetation. This influences the soil to use nutrients and improve soil fertility improving [27] the accessibility of nutrients like phosphorus and potassium, and stimulating nutrient availability, thereby improving plant resilience and root development, especially in sandy or deficient soils. At the molecular level, biochar can prime plant gene expression, upregulating defense pathways such as those involving jasmonic acid, cytokinin's, auxins, and gibberellins, while suppressing disease-related pathways [28]. The increased charge density facilitates nutrient transport, modifies soil properties, and hence promotes crop production [29]. Its effectiveness, however, depends on the kind of feedstock, the pyrolysis conditions, and the extent of its integration within the soil. The growth of plants may be hindered if volatile chemicals are not well controlled on charcoal surfaces [9]. Biochar improves soil health via processes that work together to foster the development of robust plant growth. An overview of the mechanism of biochar action in plant growth is represented in Fig. 2.

3.1. Improvement of soil physical and chemical properties

Biochar's vast surface area, porous structure, and surface charge may allow it to hold a considerable amount of nutrients such as nitrogen (N), phosphorus(P), and potassium (K). These properties reduce nutrient leaching and gas losses, which is especially useful in coarse or disturbed. Biochar's cation exchange capacity (CEC) is important for its ability to retain and finally release nutrients. CEC changes depending on feedstock and pyrolysis [30]. Biochar produced from nutrient-rich feedstocks such as manure, crop residues, at lower temperatures (<400 ° C) contains high levels of N, P, and K available to plants, directly supplementing soil fertility [31]. Manure-based biochar is particularly effective in increasing soil available P and K. Studies show a reduction in N leaching by 26% and P leaching by up to 68%, depending on biochar type and application rate [32]. In soils that are sandy or salty, when the major issue is the loss of nutrients, this is a beneficial arrangement. The dried bulk density of the soil will go up after biochar is added. This is because biochar has low mechanical strength and quickly breaks down into smaller particles. These particles will occupy the pore spaces that are already present in [33].

3.2. Soil dependent performance of biochar

Biochar consistently increases microbial biomass across sandy, clay, acidic, and saline alkaline soils, but its impact on microbial diversity and community succession is more variable [34]. Sandy and acidic soils show substantial increases in microbial biomass and diversity after biochar application, owing to their initial low fertility and pH-buffering capacity [34]. In comparison, clay soil often exhibits delayed responses due to its greater nutrient retention and buffering capacity. Alkaline and saline soils benefit from biochar's ability to reduce salinity stress and increase microbial activity. However, the magnitude of these effects depends on both the severity of salinity and the specific biochar used [35]. Over time, biochar can shift microbial community architecture, increase the fungal-to-bacterial ratio and promote beneficial functional

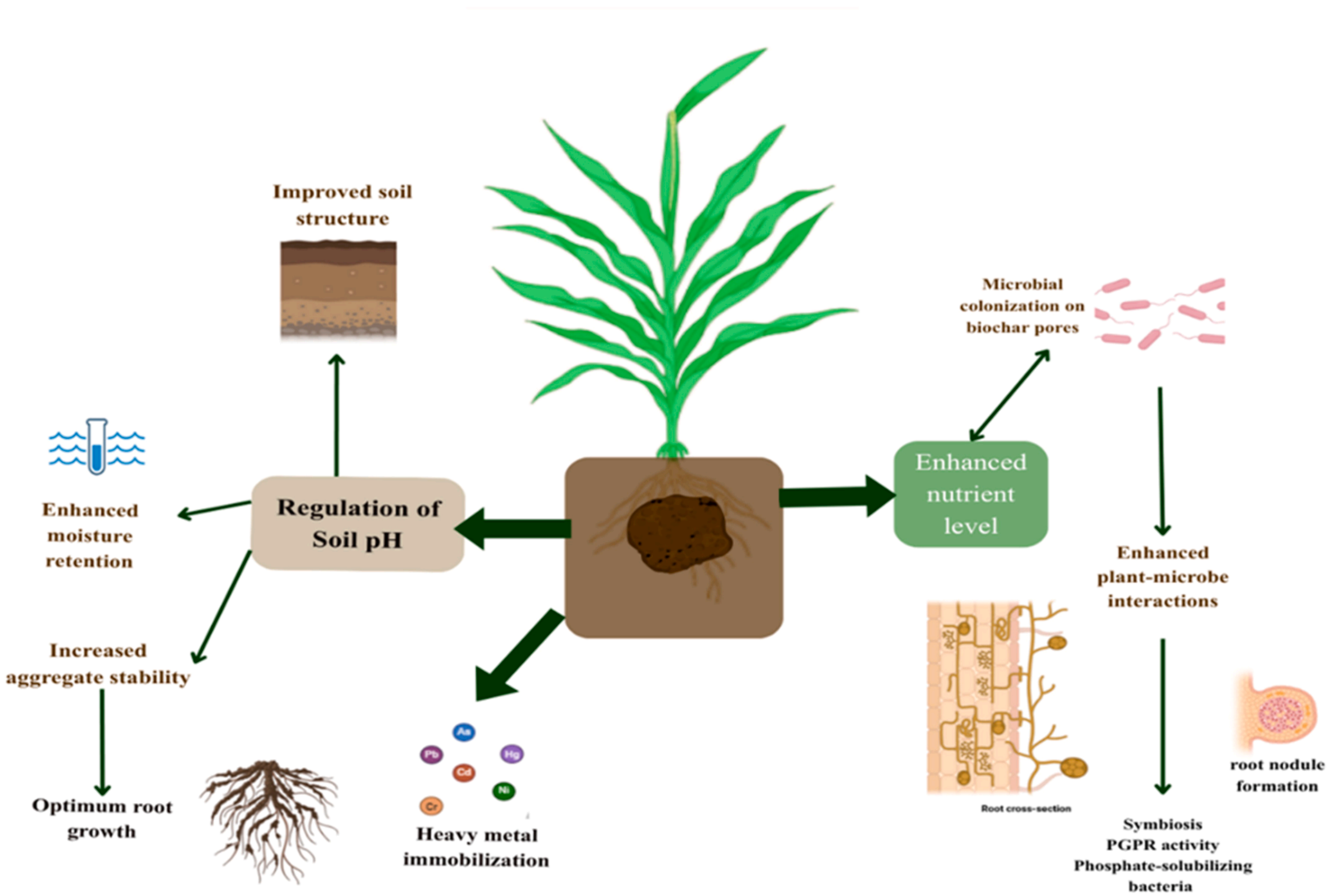

Fig. 2. Mechanism of biochar action. Schematic representation of the beneficial aspects of biochar in promoting plant growth through physical, chemical, and biological mechanisms in the soil by regulating soil pH, enhancing moisture retention, stabilizing aggregates and immobilizing heavy metals. It also enhances microbial colonization, improves nutrient availability and strengthens plant microbe interactions, ultimately promoting root growth and plant productivity [9].

groups, while also enhancing nutrient cycling and soil health [36]. These improvements in soil biological activity contribute to sustainable soil management and ecosystem restoration, supporting global sustainability objectives, such as Sustainable Development Goal 15 (SDG 15), which emphasizes the protection, restoration, and sustainable use of terrestrial ecosystems. However, long-term studies highlight that these benefits may diminish or stabilize as biochar ages in the soil. Therefore, optimizing biochar type and application strategies for different soil conditions is important to maximize positive effects on microbial succession, soil health, and overall ecosystem function [37].

Table 1
Biochar effects on microbial community and major mechanisms in different soil types.

Soil type	Biochar effects on soil properties	Microbial community composition and succession features	Notable mechanisms/ conditions (dose, feedstock)	Duration	Pot/field	References
Sandy/semi-arid	Higher pH, moisture, and SOC (+9–14%) after four years	Compositional shift; enrichment of C- and N- cycling taxa; pathogens suppressed	Effects are strongest at higher rates and linked to SOC	4 years Post single application	Field (buckwheat cropping system)	[38]
Clay soils	Improved physical conditions and nutrients	Community composition strongly regulated by porosity, moisture and nutrient fertilisation; dominant phyla Proteobacteria, Cyanobacteria, and Actinobacteria respond to dose	Clay limits immediate gains; long-term benefits are more related to aggregation and nutrient retention than large shifts	Meta-analysis (duration varies)	Mixed pot/ greenhouse and field studies	[39]
Acidic -neutral	Soil functions largely stable over a decade; long-term straw + biochar increased pH and C/N cycling functions	Bacterial diversity increased, biochar application annually, enhanced methanotrophy	Successive biochar in rice-wheat rotation improved pH, bacterial functional potential increased	10-year study	Field (paddy soil)	[40]
Saline- alkali soils	Biochar reduces pH, increases nutrients in highly alkaline fields	Enrichment of salt-tolerant and nutrient cycling taxa	Shift in assembly from homogenous to heterogeneous selection by year 3	Short-term incubation	Laboratory soil incubation	[41]
Calcareous sandy soil	Same biochar's produced smaller changes in pH and nutrients than in acidic sandy soil	Soil buffered, community shifts present but weaker, fewer changes in niche conditions	Indicates diminishing returns of biochar where baseline fertility/ buffering is higher	Meta analysis	Mixed pot/ green house and field studies	[39]

3.3. Enhanced nutrient retention and availability

Biochar functions as both a nutrient reservoir and a nutrient-cycling catalyst, particularly when derived from nutrient-rich organic feedstocks such as livestock waste. Its high surface area, porosity, and surface charge allow it to adsorb N, P, and K, reducing leaching while supporting nutrient cycling [42]. The chemical basis for this is pyrolysis-temperature-dependent: low-temperature chars retain oxygen-containing acidic functional groups (carboxyl, phenolic) that deprotonate to create negatively charged sites with high cation exchange capacity for metal cations such as K^+, Pb^{2+}, and Cd^{2+} [43,44]. As pyrolysis temperature increases, these groups are progressively lost as condensed aromatic and oxonium ($C–O^+$) structures form, generating positive surface charge and increased anion exchange capacity, enabling sorption of nitrate and chromate even at relatively high pH [44]. Nitrogen-containing groups (e.g., pyridinic or protonated amine groups) provide additional pH-dependent anion-binding sites [45]. This temperature-dependent shift in surface chemistry is the mechanistic basis for why low- and high-temperature biochar perform differently across cation- versus anion-dominated nutrient retention tasks, a distinction that is functionally important but easy to lose in a purely descriptive account.

3.4. Stress tolerance (salinity, drought, heavy metals)

Salinity and drought. Biochar's porous structure promotes water retention and reduces transpiration, improving soil water availability, nutrient uptake, and stomatal regulation under stress, thereby reducing photosynthetic damage [35]. It also tends to reduce sodium (Na^+) uptake while increasing potassium (K^+) uptake, supporting ionic and osmotic balance [46]. A central mechanism underlying these effects is modulation of phytohormone profiles- not, as sometimes stated, phytochrome regulation, which refers to an unrelated light-signaling pathway. Under salinity and drought stress, plants typically accumulate stress hormones (jasmonic acid, abscisic acid, ethylene) while growth hormones such as indole-3-acetic acid decline; biochar amendment has been reported to shift this balance toward reduced stress-hormone signaling and increased growth-hormone activity [47].

It is important to note that the specific hormonal patterns reported are largely species- and study-specific, and should not be read as a single universal signaling cascade: in tomato, biochar upregulates JA, brassinosteroid, cytokinin, auxin, and gibberellin pathways while downregulating salicylic acid (SA) signaling, consistent with JA-mediated resistance to Fusarium crown and root rot [48]. In Echinacea, biochar activates auxin and JA signaling within the broader plant hormone transduction pathway, alongside increased phenylpropanoid-derived defense metabolites [49]. In tobacco under continuous cropping, biochar elevates ABA, auxin, and JA together with their signaling genes, linked to improved antioxidant capacity and photosynthesis [50]. Notably, some of these findings (elevated ABA/JA improving resilience) sit in apparent tension with the general pattern described above (reduced stress hormones under biochar treatment); this likely reflects real context-dependence- species, stress type, and biochar formulation all modulate which direction the shift takes - rather than a contradiction in the underlying mechanism. Separately, biochar co-composted with fertilizers has been reported to optimize hormone balance by decreasing ABA and increasing SA [51], and under drought, to reduce ABA while activating SA-mediated glutathione signaling genes (*ICS1*, *NPR1*) [47]. These transcriptomic and hormonal findings are valuable as mechanistic evidence within their specific systems, but given the diversity of results across species, they should be read as illustrative case studies rather than a generalized biochar-hormone mechanism.

In the context of heavy metal contamination, biochar's functional groups and high surface area adsorb and immobilize heavy metals (Pb, Ni, Cu, Cd, Cr) via precipitation, adsorption, electrostatic attraction, and ion exchange, reducing both their mobility in soil and their availability for plant uptake [52]. This is the adsorption-chemistry mechanism. Separately and this is a distinct, downstream claim rather than part of the same mechanism, reduced plant uptake of heavy metals is associated with reduced dietary/food-chain exposure and correspondingly lower estimated carcinogenic and non-carcinogenic health risk in affected populations; this link should be stated explicitly as an inferred downstream consequence of reduced bioavailability, not conflated with the adsorption mechanism itself. Modified biochar's (e.g., MgO-loaded) show higher adsorption capacity and stability than unmodified biochar, with reported improvements of 50–70% in adsorption capacity in some studies, though performance still varies by metal type, biochar modification, and water chemistry, and engineered materials do not uniformly outperform unmodified biochar across all conditions [53]. This adsorption mechanism is well-supported by dose-specific field and pot-trial evidence: sugarcane bagasse biochar (SBB) applied at 6% w/w significantly increased rice grain and biomass yield (by approximately 45% and 58%, respectively) under cadmium-contaminated calcareous soil conditions, with Langmuir adsorption modelling confirming Cd immobilization onto the biochar surface [16,19]. Similar SBB-mediated improvements have been reported in corn grown under combined cadmium and lead contamination [54]. Overall, biochar and modified biochar represent low-cost, environmentally sustainable options for mitigating salinity, drought, and heavy metal stress, though further research is needed to optimise formulations and validate performance at field scale [55]. Across stress types, the most consistently supported mechanism is physical/adsorptive (water retention under drought; ion exchange under heavy metal stress), while hormone-mediated mechanisms under salinity and drought are well-evidenced in individual species but not yet established as generalizable across crops.

4. Biochar in early growth and seed germination

The literature reports both stimulatory and inhibitory effects of biochar on seed germination and early seedling growth. Rather than treating this as an unresolved inconsistency, these findings are more usefully organised around three governing factors that determine which outcome dominates in a given study: (i) feedstock and pyrolysis temperature, which determine residual phytotoxic compound content; (ii) application dose; and (iii) species-specific sensitivity.

Dose and species dependence. In rice and capsicum, biochar treatment at 15 t/ha significantly increased seed germination and early growth traits, including shoot elongation and root-to-shoot ratio [57]. In contrast, a study testing biochar derived from wood, paper sludge/wheat husk, and sewage sludge across five species (cress, lentil, cucumber, tomato, lettuce) found no significant overall germination effect, with inhibitory effects specific to wood biochar in several species and paper-sludge biochar in lettuce, indicating that outcomes depend on the specific feedstock–species pairing rather than on biochar application generally. In some cases, root growth was unaffected by biochar treatment, while in others, both leaf and shoot development were fully suppressed [58], underscoring that inhibitory and stimulatory effects can co-occur across species within the same study rather than representing a general biochar effect.

Phytotoxicity mechanisms and their dependence on production conditions. Where biochar shows inhibitory effects, this is generally attributed to residual phytotoxic compounds, polycyclic aromatic hydrocarbons (PAHs) and heavy metals that induce oxidative stress and impair seedling viability [59]. Critically, the concentration of these compounds is itself a function of pyrolysis conditions: PAH content is typically higher in biochar produced at lower pyrolysis temperatures or with incomplete combustion, whereas higher-temperature pyrolysis reduces PAH content but can concentrate heavy metals present in the original feedstock. This means phytotoxicity is not an inherent property of "biochar" as a material, but a production-condition-dependent variable, a distinction the broader literature does not always make explicit, and one that should guide feedstock/process selection rather than

Table 2
Mechanisms of biochar action and their observed effects in soil and plants.

Stress type	Biochar mechanism	Observed Effects	Strength/consistency of evidence	Duration	Plot/field	References
Heavy metal stress	Immobilisation of toxic metals via surface adsorption and complexation; alters microbial diversity and redox potential; raises soil pH, lowering metal bioavailability. Modified biochar (e.g., corn straw biochar) enhances remediation efficiency.	Decreased Cd, Pb, and as uptake by plants; improved soil quality; reduced metal toxicity and oxidative stress in plants. Downstream inference: lower plant uptake is associated with reduced dietary exposure, and correspondingly lower estimated carcinogenic/non-carcinogenic health risk in populations consuming crops grown on treated soil.	High adsorption chemistry is well-established and directly measurable; the health-risk link is a reasonable but inferred downstream consequence, not a directly measured outcome in most cited studies	2 years (4 crop cycles), single application	Field	[13,46]
Water-holding/drought stress	Increases soil water-holding capacity and aggregation; improves root structure for deeper water uptake; enhances microbial activity supporting nutrient cycling; boosts antioxidant enzyme activity	Sustained soil moisture and plant hydration; improved plant morphology/physiology; reduced oxidative damage; improved wheat growth with reduced Cd accumulation under combined drought + Cd stress	High for the physical water-retention mechanism; the antioxidant/hormonal component is less consistently characterised across species	Seedling- stage controlled stress trial; 30 days pre-salinisation + amendment, fruit assessed at 90 days after transplanting	Pot/ controlled growth chamber	[30,56]
Salinity stress	reduces Na^+ uptake, enhances K^+ uptake, neutralises soil pH, maintains ionic balance and osmotic stability. Biological mechanism: stimulates antioxidant enzymes (SOD, POD, CAT); promotes beneficial microbial communities	Enhanced antioxidant defence; reduced oxidative damage; improved stress tolerance in salt-affected soils	Ionic/osmotic mechanism is well-supported; enzyme/microbial effects are documented but vary by species and biochar type, should not be read as a single universal hormonal pathway	28 days (15-day stress exposure, foliar nano biochar at 14/21/28 days after sowing	Pot/ green house	[46]

treating phytotoxicity as a fixed risk of biochar use in general.

4.1. Quantitative findings and their limits

Some bioassays report large relative effects; for example, corn starch residue incubated with leached biochar showed a 6- to 12-fold increase in radicle length in one study [60]. This is a relative measure; without the reported absolute baseline radicle length or control conditions, the magnitude should be interpreted cautiously rather than presented as a general indicator of biochar's germination-promoting potential. Similarly, biochar applied at 1.5% concentration has been reported to improve germination rate by 13% and seedling vigor by 85%, while modestly reducing mean emergence time and increasing germination rate by approximately 3% [61], again a single-study, single-dose finding rather than an established dose-response curve. In one study, altered soil nutrient availability following Kadam biochar application was associated with increased shoot and root biomass, though the specific nutrient pathway responsible was not established in that study. Across studies, moderate biochar doses tend to support antioxidant enzyme activity and stress tolerance during early growth, while higher doses more consistently induce oxidative damage; as a general reference point, application rates around 20 t/ha have been reported to reduce water-stress impacts in young soybean without inducing toxicity [62], though this threshold should not be generalized across feedstocks or species without further validation.

Biochar's effect on germination and early growth is best understood not as a fixed positive or negative outcome, but as the product of interactions among application rate, the phytotoxic compound load determined by the feedstock and pyrolysis temperature, and species-specific tolerance. Within a moderate dose range and using biochar with low residual PAH/heavy metal content, the evidence points toward enhanced germination and early seedling vigor via improved moisture retention and nutrient supply. Outside that range, at higher doses, or with biochar retaining high phytotoxic compound content, inhibitory effects dominate. Reframing the evidence around these governing variables, rather than around promotion versus inhibition as competing findings, resolves most of the apparent contradiction in the literature and should guide feedstock and dose selection for future germination studies.

5. Biochar in crop productivity

The impact of biochar on crop output has been regularly shown in cereal, horticultural and legume systems; however, feedstock, pyrolysis temperature, application rate and the initial fertility of the soil to which it is applied all influence the response’s size and even direction. In low-fertility or sandy soils, where biochar’s enhancement of nutrient retention, water-holding capacity and soil organic carbon has the most potential to operate, yield increases are most consistent; in already-fertile soils, where these limitations are not restricting, gains are less pronounced. The reaction is crop-specific rather than consistent among cereals: rice responses are less or not statistically significant, whereas maize and wheat exhibit the biggest improvements (about 20% and 12% respectively) [34]. While maize and wheat are more frequently grown on the drier, lower-fertility soils where those qualities are most important, rice paddy soils are generally water-saturated and nutrient-buffered, which reduces the marginal benefit of biochar’s water and nutrient-retention properties. In the first one to two seasons, short-term yield boosts of 10–20% are typical; in studies that have followed longer (5–10 years), benefits are sustained and, in some cases, amplified to as much as 31%. This is attributable to the cumulative build-up of soil organic carbon and the ongoing reduction in bulk density [63]. Since soil type, climate and management practices all affect how biochar ages in soil over a ten-year period, these longer duration figures represent an upper bound demonstrated under favourable conditions rather than a general expectation across soils and climates. They are derived from a small number of site-specific trials. These results are further influenced by feedstock quality: at equivalent application rates, manure-based and high phosphorous biochar (>1% P, >70% C, >50 m^2/g surface area) yields greater gains than wood-based biochar, which is consistent with the additional nutrient contribution manure-derived biochar provides beyond its structural and retention effects [13]. Since the benefits is linked to the particular nutrient composition of manure rather than a general characteristic of biochar, it should not be extrapolated to other feedstock-crop combinations without direct testing. This feedstock advantage has been specifically shown for maize, foxtail millet, sorghum and millet under farmyard-manure derived biochar [64,65].

Through enhanced soil health and nutrient uptake, biochar has increased productivity in horticulture systems for temperate and Mediterranean fruit crops like apples, grapes and cherries. Similar to cereals, this benefit is anticipated to increase with the baseline soil's nutrient or water limitation; however, this link has not been empirically evaluated across horticulture systems. Compared to cereal responses, legume responses to biochar are typically greater and more consistent, with meta-analyses showing average yield increases of 13–32% over three years of continuous cropping, occurred under specific stress or management conditions rather than as a baseline effect, indicating that biochar's benefit to legume is amplified when the crop is already under abiotic or soil-fertility constraint [66,67]. This tendency is reinforced by the notable improvements in cowpea, peanut, lentil and mungbean, particularly on degraded or nutrient-poor soils. Co-application with biofertilizers (rhizobium), vermicompost, or mineral fertilizers further boosts yield, nitrogen fixation and nodulation in lentils and chickpeas, consistent with biochar increasing the microbial and nutrient cycling conditions that promote these symbioses [67,68].

The yield advantages rise with application rate up to a threshold, after which the impact plateaus or reverses, according to a recurrent trend in the research compiled in Table 3. This threshold often falls between 10 and 20 t/ha in non-saline soils; rates over around 20 t/ha have been shown in certain studies to reduce or reverse the benefit, most likely due to excess alkalinity, nutrient imbalance, or over-adsorption of plant available nutrients at high biochar loading [69]. The optimal range shifts significantly higher in saline soils, to about 40–50 t/ha, with reductions reported above 50 t/ha [70]. This indicates that the benefit of biochar in saline soils is partially due to sodium adsorption and salinity buffering, a mechanism that requires higher loading to saturate. These two thresholds are not incompatible once soil salinity is considered as the moderating component; in order to facilitate direct comparison across soil types, future research should report salinity status in addition to application rate. Farmers are still not using biochar on a commercial basis, despite these proven yield gains [71]. The economics of feedstock collection and pyrolysis, the requirement that yield benefit be sustained over several seasons to offset upfront application cost and the logistical demands of field-scale application are practical barriers that function independently of biochar's proven biological performance, so this is unlikely to reflect a lack of evidence for yield benefit. The diverse biochar sources, their application rates and the ensuing effects on crop yield and growth performance across several plant species are shown in Table 3.

Application rates reported as % w/w are not directly comparable to t/ha values without the bulk density and incorporation depth of the original study. Converted from Mg/ha (1Mg=1t); unit equivalence only, no additional assumption applied. Across studies, the optimal biochar application rate is not a single fixed value but depends on soil salinity status: approximately 10–20 t/ha in non-saline soils versus 40–50 t/ha in saline soils, with yield reduction reported above these respective thresholds in both cases [69].

Table 3
Effect of different biochar feedstocks and application rates on crop productivity.

Biochar type/ Feedstock	Application rate	Crops	Effect on crop productivity	Refrences
Rice straw, Corn stalk	1–4 t/ha	Corn, Peanut, Sweet potato, Wheat	Yield increased 5–20%, higher rates (4 t/ha) gave ~20% increase	[72]
Conocarpus (woody)	4–8% w/w	Tomato	Increased vegetative growth and yield by 14 –43%	[73]
Maize cob, Prosopis, Coconut shell	7.5–15 t/ha	Maize	Highest yield at 15 t/ha; yield increased with application rate	[74]
Mixed hardwood	5% w/w	Wheat	Increased growth and final yield	[74]
Acacia spp. (Woody)	50 + 50 Mg/ ha (over 2 seasons)	Maize, Soybean (rotation)	Yield increase: maize + 1.2 Mg/ ha, effect persisted 10 years	[75]
Rice husk, Cacao shell	5–15/ha	Maize	Cacao shell biochar (15t/ha) had a stronger, longer-lasting yield effect than rice husk	[76]
Sawdust, rice straw, coconut shell	1–2%	Dictyophora rubrovolvata (mushroom)	Rice straw/ coconut shell increased yield by more than 16%; sawdust at high input reduced yield	[77]
herbaceous biochar, manure, wood	1–20 t/ha	Maize, Wheat, rice, legumes, Vegetables, oil plants	Manure biochar: yield + 42%; wood: + 22%; best for crash crops, acidic/ sandy/clay soils	[78]
Various feedstocks (general)	1–10 t/ha (optimal, non-saline)	Maize, wheat, rice, soybean	Yield increases 4.9–48.4%, best at 1–10 t/ha, > 20 t/ha may reduce effect	[69]
Various feedstocks (general)	40–50 t/ha (saline soils)	Rice, wheat, maize, and cash crops	Yield increased in salt-affected soils, optimal at 40–50 t/ha, > 50 t/ha may reduce yield.	[70]

6. Plant physiological & biochemical responses

This section focuses on the physiological and biochemical responses that have a confirmed or probable association with biochar amendment, categorized into three areas: water relations and photosynthetic efficiency under abiotic stress, modulation of oxidative stress and regulation of nutrient uptake and metabolism. The general background of stress physiology is presented solely to elucidate the process by which biochar operates, rather than as an independent discourse.

6.1. Photosynthetic efficiency and water use

Salinity and drought both impede crop productivity via intersecting physiological mechanisms: increased root-zone salt concentration hinders metabolic development, photosynthesis and nutrient synthesis, whereas drought stress diminishes biomass accumulation, photosynthetic efficiency and stomatal conductance by restricting leaf chlorophyll concentration [79]. Biochar mitigates both stressors via a singular fundamental property rather than through distinct stress-specific mechanisms: its elevated porosity and surface area enhance soil water retention and nutrient preservation, thereby buffering the root zone against the water scarcity associated with drought stress and reducing the salt concentration linked to salinity stress [80]. The reason biochar is effective as a long-term solution for restoring salt-affected soils and improving water and nutrient retention during drought is that it works through the same underlying mechanism: enhancing soil water and nutrient retention. This shared pathway, rather than separate physiological effects for each stressor, explains biochar's benefits in both situations [81].

6.2. Modulation of oxidative stress

Salinity and high temperature stress elevate the generation of reactive oxygen species (ROS), which impair photosystem II activity and damage cellular macromolecules such as DNA, lipids and proteins [82, 83]. Plants mitigate this using antioxidative enzymes, including superoxide dismutase, glutathione reductase and peroxidase, facilitated by the thioredoxin system, which provides electrons enabling thiol-dependent antioxidant enzymes to eliminate ROS at elevated reaction rates [84]. Currently, direct evidence indicating that biochar amendment influences antioxidant mechanisms is scarce; the more substantiated interpretation is that biochar mitigates ROS accumulation indirectly by alleviating the salinity and drought conditions, which initially provoke excessive ROS production, rather than directly affecting the antioxidant enzyme system. This distinction is crucial for accurately attributing the benefits of biochar to a soil-level mechanism rather than an unverified direct biochemical effect.

6.3. Clarification of nutrient uptake, metabolic regulation and nutrient content

Potassium (K^+) explains the physiological advantages derived from biochar's impact on soil: K^+ facilitates osmoregulation, cell elongation, stomatal regulation and the distribution of nitrates from roots to vegetative tissue, proving essential for sustaining these functions during drought conditions [85]. Biochar's role is indirect; its porous structure and cation exchange capacity enhance the retention and availability of K^+ and other nutrients in the root zone, so supporting existing physiological processes rather than creating a novel one [86]. The function of nitrogen retention is most effectively comprehended when compared to traditional fertilizer applications. Chemical fertilizers, although extensively utilized to compensate for restricted arable land and increasing food demand, are linked to low use efficiency, soil degradation, yield reductions and water eutrophication when applied in excessive amounts [87]. Organic fertilizers mitigate numerous difficulties and enhance yield, soil fertility and quality; yet, they generally release nutrients at a rate insufficient to satisfy the immediate absorption requirements of crops [88]. Biochar occupies a unique role between these two: as a pyrolyzed organic material, it enhances soil organic carbon and moisture retention, thereby improving the soil's inherent capacity to facilitate nutrient cycling and crop growth, rather than serving as a nutrient source or a rapid release fertilizer alternative in its own right [89]. This differentiation is crucial for accurately interpreting the elemental makeup of biochar. Biochar comprises carbon, hydrogen, sulfur, oxygen and nitrogen; yet this represents the elemental makeup of the biochar material rather than a reservoir of plant-available nutrients. Biochar affects plant nutrition mainly by enhancing the soil's ability to retain and cycle nutrients, including the three essential macronutrients: nitrogen, phosphorous and potassium, rather than by directly providing these nutrients in a form accessible to plants. This nutrient cycling function, along with its recognized roles in carbon sequestration, heavy-metal mitigation and soil moisture restoration, underpins biochar's significance in agriculture and soil management [90].

7. Synergistic application

Because of its porosity, cation exchange capacity and ability to retain water and nutrients, biochar is increasingly being co-applied with fertilizers, compost and microbial inoculants rather than utilized alone. Rather than discussing the general biology of the organisms or fertilizers involved, the discussion that follows concentrates on how biochar specifically alters the performance of each co-applied input.

7.1. Biochar with fertilizers and compost

Increasing inorganic nutrient supply to offset the impacts of conventional fertilizers tends to exacerbate rather than alleviate nutrient depletion and greenhouse gas emissions. An option is provided by biochar, which adds phosphorous, potassium, zinc, iron, magnesium and calcium to the soil and enhances its pH, cation exchange capacity, electrical conductivity, organic carbon content and total nitrogen [91]. Biochar and fertilizer are combined directly in more recent formulations. By retaining soil nitrogen better than urea alone, a powdered biochar mineral urea composite (Bio-MUC) increases root growth by 25% and shoot growth by 14% [92]. In comparison to traditional chemical fertilizers, biochar compound fertilizers (BCF), which are made from feedstocks such as peanut kernel, maize husk, pig manure compost and municipal waste, enhanced nitrogen use efficiency and decreased greenhouse gas emissions in rice cultivation. These findings show that adding biochar to compost and fertilizers increases soil fertility and yield while lowering the environmental costs associated with using chemical fertilizers alone.

7.2. Biochar with microbial inoculants

7.2.1. Biochar with plant growth-promoting rhizobacteria (PGPR)

Biochar's porous structure and stable carbon matrix create protective microhabitats that shield soil microorganisms from predation, desiccation, and temperature stress, improving their survival [71]. Rather than listing the full range of taxa reported across studies, they can be grouped functionally: nutrient-cycling and pH-adapted taxa (*Actinobacteria, Proteobacteria, Gemmatimonadetes*, arbuscular mycorrhizal fungi) tend to increase in relative abundance following biochar amendment [93]; biocontrol- and growth-promoting taxa (*Pseudomonas, Streptomyces, Bacillus*, along with phosphate-solubilizing and nitrogen-fixing bacteria) benefit from the structural protection biochar provides for colonization [71]. This functional shift is generally associated with improved nutrient cycling and disease suppression, though the effect is context-dependent rather than universal, varying with soil type and biochar characteristics [71]. Over time, communities tend to shift toward more oligotrophic, functionally stable consortia with reduced representation of potential pathogens [38]. Biochar's influence on microbial gene expression and plant-microbe signaling has also been reported [94], but this remains an emerging area where mechanistic detail is still limited to specific study systems; more field-based, longitudinal work is needed before this can be generalized as a core mechanism [95].

Biochar and PGPR are increasingly utilized in conjunction, as each helps mitigate the other deficiencies under stress conditions [96]. PGPR enhance plant growth directly or indirectly by secreting regulatory chemicals, enzymes and phytohormones, as well as by establishing systemic resistance to pathogens; their stimulatory effect is most pronounced in nutrient-deficient soils and diminished in soils with high fertility. Biochar's particular role in these combinations is to furnish with a substrate; its elevated surface area and nutritional composition enhance PGPR viability and functionality, hence immediately augmenting PGPR efficacy [97]. The most evident illustration of this is a specific application outcome rather than a universal principle: soil nitrate content rose by 87% when biochar (2% w/w) and PGPR (*Paenibacillus polymyxa* and *Bacillus amyloliquefaciens*) were applied concurrently, compared to nitrogen applied in isolation [98]. This result pertains exclusively to particular strain-biochar combination and should not be interpreted as a generic effect size of PGPR-biochar. The independently documented advantages of PGPR inoculation alone, enhanced apple root development with IBA/carbohydrates, chickpea growth and nodulation with phosphorous enriched compost, and increased cotton yield/rhizosphere populations, illustrate the overall effectiveness of PGPR. However, these findings were not evaluated in conjugation with biochar co-application, thus reinforcing the efficacy of PGPR rather than elucidating the specific interaction between biochar and PGPR.

PGPR function via direct mechanisms (nutrient supply, phytohormone modulation) and indirect mechanisms (competition, antimicrobial metabolite synthesis, induced systemic resistance) [99]. The efficacy and intensity of PGPR action are contingent upon host plant genotype, developmental stage, soil type and environmental variables [100], indicating that the aforementioned 87% result is likely to fluctuate based on strain, soil and crop rather than being universally applicable.

An efficacious PGPR strain for biochar co-application must be rhizosphere-competent, resilient to the physicochemical conditions established by biochar and capable of coexisting with the indigenous microbial population without succumbing to competitive exclusion [101]. Fig. 3 illustrates the synergistic effect of coupled PGPR-biochar application in alleviating drought, salinity and heavy metal stress: biochar enhances soil structure, nutrient cycling and water retention, which in turn promotes plant photosynthesis, antioxidant activity and stress resilience [100]. Fig. 4 depicts the direct and indirect mechanisms of action of PGPR, independent of biochar-direct growth enhancement via nutrient absorption and indirect protection through pathogen competition and the induction of systemic resistance [102]. The durability of introduced PGPR strains when biochar is applied at scale is a major unknown in applying these combined-application results to the field. Biochar has been demonstrated to improve PGPR survival and growth when compared to unamended soil using real-time PCR (qtPCR) to track inoculated PGPR strains in agricultural soils. However, tracking techniques are still required to identify the precise elements controlling strain persistence and interactions with native soil microbiota over time [103]. This cautious framing is supported by field-scale evidence: in three-year field trials on tomatoes that combined biochar with microbial biofertilizers, the resulting rhizosphere bacterial community showed a combination of the introduced consortium and the pre-existing native community rather than total replacement by inoculated strains. This suggests that introduced PGPR must establish alongside, not in place of, the native microbiome [104]. According to these results, field persistence and native-community competition should be considered open variables that requires longer-term monitoring, while pot-study efficacy figures like the 87% nitrate increase mentioned above should be regarded as an upper bound achievable under controlled inoculation conditions.

7.2.2. Biochar with Mycorrhizae

Arbuscular mycorrhizal fungi (AMF) establish a significant microbial association with biochar. AMF colonization enhances phosphorous absorption about tenfold compared to root hairs alone and bolsters resistance to various biotic stresses [105], while also generally augmenting pollution resilience, water absorption, mineral nutrition and soil structure [106]. Similar to PGPR, biochar alters the environment in which AMF function: the co-application of biochar with AMF enhances plant metrics, soil enzyme activity and disease resistance beyond the effects of AMF inoculation alone [107]. In phosphorous deficient soils, the combination of biochar with microbial inoculants significantly enhances corn growth and nutrient absorption [108].

Biochar's porosity and cation exchange capacity keep root-exuded compounds like sugars, amino acids, organic acids and strigolactones, adjacent to the root surface, while PGPR are independently documented to stimulate AMF spore germination. The application of combined PGPR and AMF, independent of biochar, enhances yields in wheat, rice and black gram by as much as 41%, along with increases in biomass, plant height, grain number and grain weight compared to non-inoculated plants [109]. Reports indicating that the incorporation of biochar into this combination enhances these benefits should be noted, similar to the PGPR-biochar data previously mentioned, as evidenced for particular systems rather than a universal three-way principle.

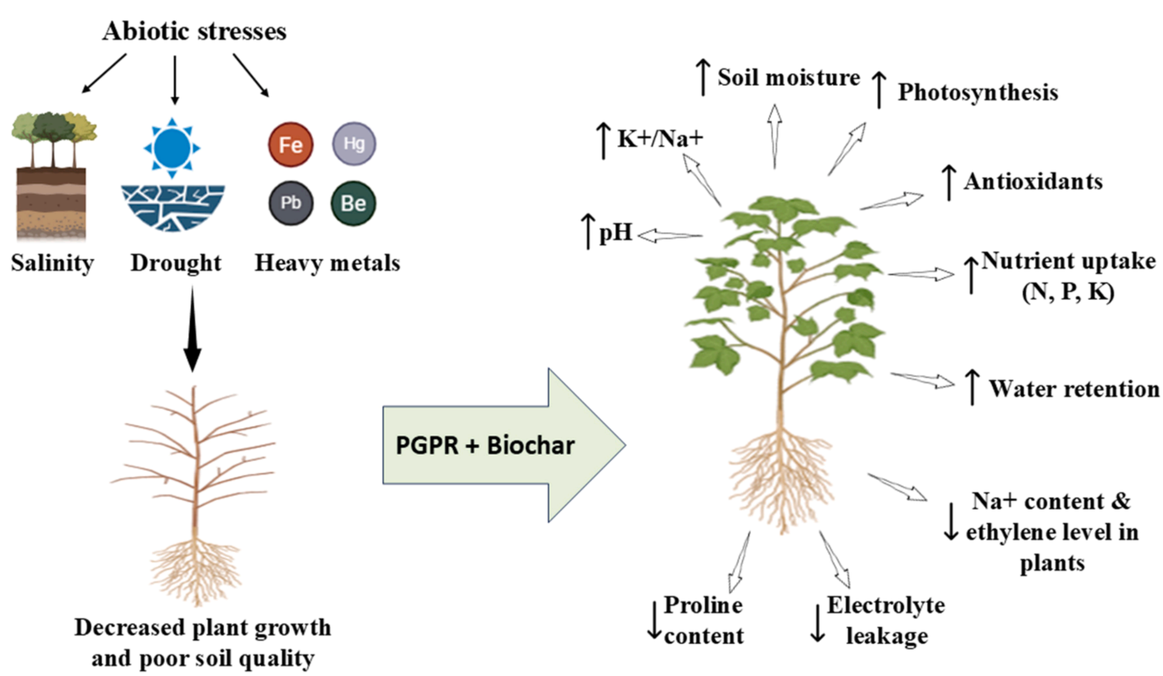

Fig. 3. Schematic representation showing the effect of plant growth-promoting rhizobacteria (PGPR) and biochar in alleviating abiotic stresses such as salinity, drought and heavy metals. Their combined application improved soil properties, enhances nutrient uptake, photosynthesis and antioxidant activity, while reducing Na^+ accumulation and stress indicators, thereby promoting plant growth and soil quality [100].

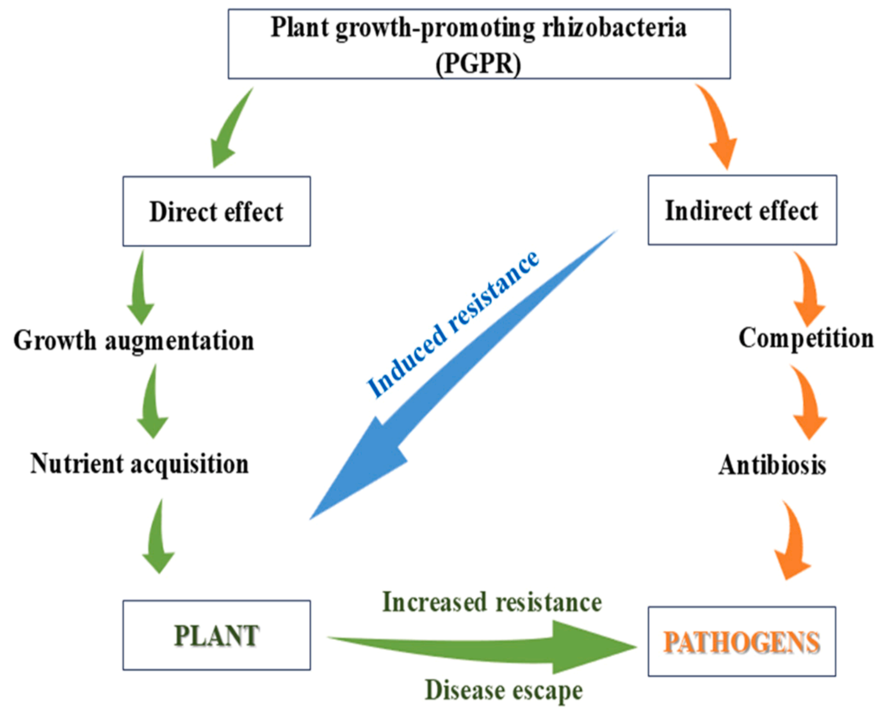

Fig. 4. Mechanism of plant growth-promoting rhizobacteria (PGPR) in enhancing plant health and resistance. PGPR enhances plant growth through direct effects such as growth augmentation and improved nutrient acquisition and indirect effects including competition with pathogens and production of antimicrobial compounds. These interactions stimulate induced systemic resistant in plants, leading to increased resistance and reduced pathogen infection [102].

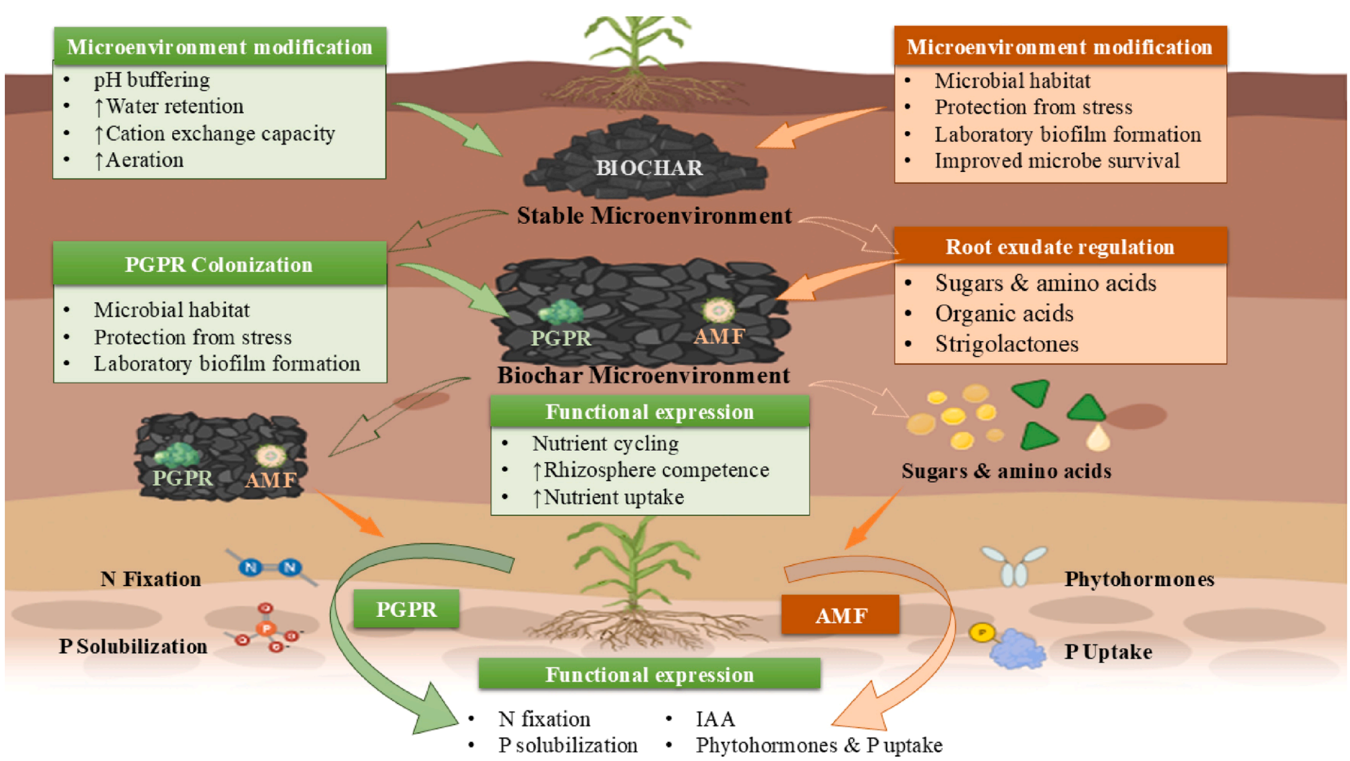

Fig. 5. Conceptual model illustrating the synergistic interaction between biochar, PGPR (Plant growth-promoting rhizobacteria) and AMF (Arbuscular mycorrhizal fungi) in the rhizosphere. Biochar alters the soil microenvironment by enhancing pH buffering, water retention, aeration and cation exchange capacity, while its porous structure provides ecological niches that support microbial colonization and biofilm formation. It also regulates root exudate release (sugars, amino acids, organic acids, strigolactones), improving microbial recruitment and activity. These combined effects promote functional expression such as nitrogen fixation, phosphorous solubilization, phytohormone production and enhanced nutrient uptake, ultimately supporting plant growth [109].

8. Limitations and potential risks

Although the advantages of biochar are well-documented throughout this review, there are some risks associated with its use. These include nutrient immobilization at high doses, pH overcorrection, contaminant retention from poorly controlled pyrolysis and effects on soil biota and weed growth, all of which are covered in detail below.

8.1. Influence of feedstock and pyrolysis

The pyrolysis temperature and the type of feedstock used to produce biochar affect the final product's physicochemical characteristics, which change when applied as a soil amendment. Burning organic waste produces biochar, an extremely stable carbon-based substance. The carbon content of biochar made by high-temperature, low-oxygen pyrolysis techniques is high. It is composed of "fixed carbon"-stable, aromatic molecules that are impervious to microbial degradation. Together with a small number of macronutrients in the feedstock, this carbon accumulation and the release of less stable organic molecules-particularly based on wood, make biochar extraordinarily stable and carbon-rich [110]. The principal factor governing this stability is the molar H/C_{orm} ratio (with ≤ 0.7 established as the accepted stability threshold); feedstocks and pyrolysis conditions that reduce this ratio result in more carbon stable, long-lasting biochar, whereas conditions that increase the ratio produce biochar that is less stable but preserves a greater portion of the original feedstocks nutrient content. The Fig. 6 represents the various organic materials utilized as feedstock in biochar production. Common sources include agricultural residues (such as rice husk and straw), wood waste (branches, barks, sawdust), animal manure, municipal and industrial organic waste, and fuel crops. The various biochar feedstock materials like agricultural residues, wood chips, manure, corresponding pyrolysis conditions, and their observed impacts on soil physical, chemical, and biological parameters are listed in Table 4.

The type of feedstock and pyrolysis conditions influence biochar's impact on soil aggregation, although findings are inconsistent: wood-derived biochar has been demonstrated to enhance soil aggregate stability and foster microbial activity, whereas other research presents conflicting aggregation results based on specific soil characteristics. Additionally, applications in forest soils have indicated a reduction in bulk density and an increase in aggregate stability, notwithstanding this variability [9]. This mismatch underscores that aggregation benefits, such as carbon stability, are contingent upon the precise feedstock-pyrolysis-soil combination rather than being an inherent characteristic of biochar universally.

8.2. Economical and practical field application factors

Beyond biological performance, studies based on pots and greenhouse fail to account for the production economics and logistics that limit field-scale deployment of biochar. The costs associated with feedstock collection, drying and pyrolysis, especially at the higher temperatures linked to more stable, high-performing biochar, vary significantly depending on the type of feedstock, local energy prices and production scale. These costs are rarely reported alongside agronomic results in the literature reviewed here. Since biochar's high carbon stability means it is not consumed like a conventional fertilizer and does not require annual re-application, its yield benefit usually needs to be maintained over several growing seasons to offset the initial application cost. This trade-off is advantageous over the long run but may deter smallholder farmers operating on a single-season-cost-benefit horizon. Additionally, practical field application is different from pot studies in that, regardless of the proven biological benefit of biochar, adoption is determined by logistical factors such as even application across variable-topography fields, integration with current tillage practices and compatibility with mechanized spreading equipment. This is made worse by the fact that the majority of the studies reviewed above are short-term (a single season to a maximum of two to three years); there are still few truly long-term field trails (>5 years) that track biochar persistence, cumulative soil-carbon change and yield stability across seasons and climatic conditions.

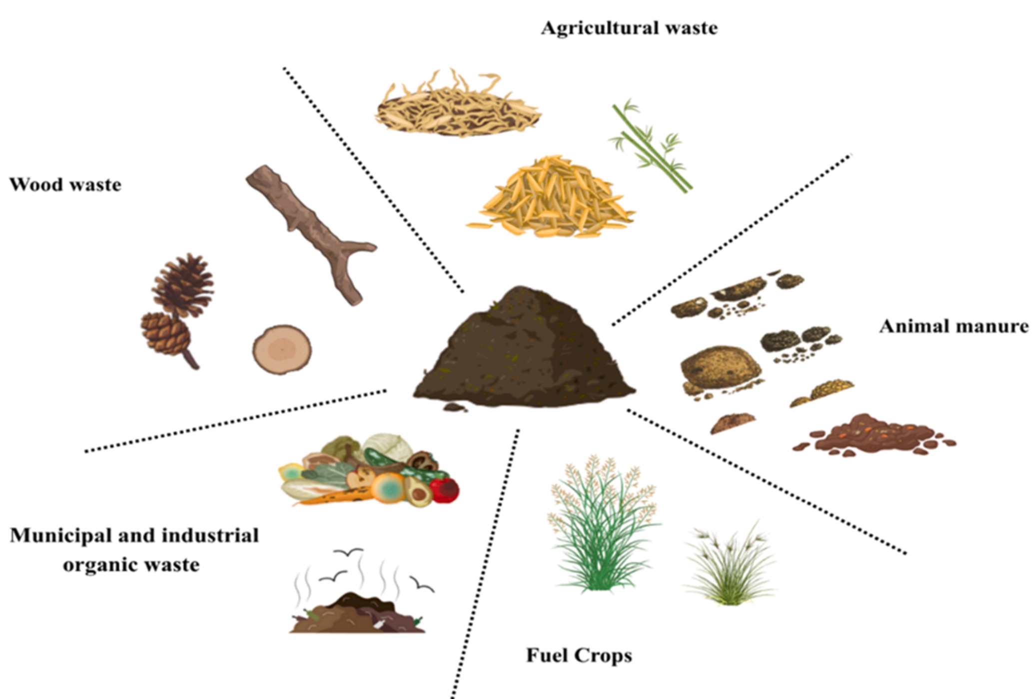

Fig. 6. Different feedstock sources used for biochar preparation. The variety of feedstocks presented agricultural residues, wood waste, animal manure and municipal/industrial organic waste, demonstrates that biochar properties cannot be universally applied across studies; the composition of the feedstock, rather than pyrolysis alone, is a principal factor influencing the physicochemical characteristics of the resultant biochar [110].

Table 4
Overview of different feedstocks, pyrolysis processes, and their effects on soil properties and tree-based crop productivity.

Feedstock type	Pyrolysis process/ temperature	Crop or tree studied	Soil/crop response	References
Rice husk	Slow pyrolysis (450 °C)	*Eucalyptus grandis*	Enhanced soil pH and cation-exchange capacity	[111]
Acacia wood	Slow pyrolysis (500°C)	*Acacia mangium*	Improved soil fertility and microbial activity	[112]
Sugarcane bagasse	Slow pyrolysis (550 °C)	*Coffea arabica*	Increased soil organic carbon and root biomass	[113]
Coconut shell	Slow pyrolysis (600°C)	*Cocos nucifera*	Improved soil porosity and nut yield	[114]
Poultry litter	Slow pyrolysis (400°C)	*Hevea brasiliensis*	Increased soil nutrients like sodium, potassium, phosphorous and latex yield	[115]
Wood waste	Gasification (700°C)	*Mangifera indica*	Enhanced carbon sequestration and fruit yield	[116]
Mixed agricultural residues	Slow pyrolysis (550°C)	*Moringa oleifera*	Improved moisture retention and growth rate	[52]
Corn stover	Slow pyrolysis (500°C)	*Tectona grandis*	Enhanced soil structured and biomass production	[117]
Agri-food processing residues	Varies across constituent studies	Multiple (European field studies, 2014–2024)	Improved soil physical, chemical and biological properties; effects on nutrient leaching and feedstock- and process-dependent	[118]
Mushroom cultivation residue (*Flammulina velutipes*)	300°C (biomass optimum); 400°C (pH/ organic matter optimum)	Cucumber (seedling stage)	Rise in soil pH 1.17 units, organic matter + 90 g/kg, biomass + 73% at 300°C vs. control	[119]

8.3. Dose dependent risks and reconciling nutrient retention

The nutrient-retention ability of biochar, typically regarded as advantageous for minimizing nutrient loss, becomes a constraint at elevated application rates. The identical adsorption of phosphorous and nitrogen that mitigates long-term nutrient loss can, when biochar is excessively applied, sequester these nutrients beyond the reach of plants and microbes, especially in soils already lacking in nutrients [120]. This is not a contradiction but a dose-dependent alteration in the same mechanism: retention is advantageous within an adequate application range and becomes a constraint once biochar's adsorption capacity surpasses the soils nutrient buffering requirements. Establishing this threshold necessitates consideration of soil type, inherent fertility and biochar production attributes, as no singular application rate is universally safe or advantageous. A corresponding dose-dependent impact is observed with soil ph. Alkaline mineral ash in biochar can significantly elevate soil pH at elevated application rates, diminishing the availability of micronutrients like iron, manganese and zinc and modifying the rhizosphere microbial community; conversely, this alkaline characteristic is advantageous at moderate application rates in acidic soils [121]. Both effects arise from the identical pH-buffering characteristics; only the treatment rate and the initial soil pH dictate the resulting consequence.

The risk of contaminants is contingent upon dosage and specific conditions, rather than being universally applicable. Biochar generated under inadequately regulated pyrolysis conditions may retain polycyclic aromatic hydrocarbons (PAHs), heavy metals and dioxins from the original feedstock [121]. Contaminant levels are primarily influenced by pyrolysis temperature, residence time and feedstock purity. The quality standards outlined in Section 8.3 establish enforceable limits for these substances; verified adherence to these limits serves as the appropriate indicator of low-risk biochar. Conversely, non-compliant products, often resulting from low-temperature or inadequately controlled pyrolysis of contaminated or heterogenous feedstock, constitute the higher risk scenario identified as a limitation in this review. Documented impacts on soil biota, insect demographics and weed proliferation exhibit a consistent trend: diminished microbial activity, compromised earthworm vitality or decreased populations of soil-dwelling fauna, alongside diminished insecticide effectiveness and in certain instances, expedited weed growth, have been specifically linked to aged or high-dose biochar applications rather than the general use of biochar [67,68]. These impacts should be seen as evidence that the ecological impact of biochar is contingent upon application rate and age, rather than as a blanket condemnation of biochar as a soil additive. Establishing suitable biochar application thresholds, informed by soil type, crop system and biochar production attributes, is crucial for maximizing biochar's agronomic advantages while mitigating dose-dependent hazards.

8.4. Quality standards, classification and certification of biochar

Although the type of feedstock and thermochemical conditions have a significant impact on the quality of biochar, the lack of consistent, legally binding criteria continues to be a major obstacle to its widespread use. The International Biochar Initiative (IBI) standard, the European Biochar Certificate (EBC), the UK Biochar Quality Mandate (BQM), the Australia New Zealand Code of Practice (ANZBI), the Chinese Agriculture Biochar Standard (CNAIS) and the Singapore Standard (SGS) 12814 [122,123] are among the voluntary schemes that currently define acceptable biochar. The two most popular schemes, IBI and EBC, both define core product parameters (minimum organic carbon content, $H/C_{orm} \leq 0.7$ as a stability index and in certain cases O/C_{orm} thresholds, limit values for heavy metals and organic pollutants like PAHs and basic agronomic indicators (pH, electrical conductivity, ash and nutrient content) [124,125]. Both approved soil application and long-term carbon sequestration claims require proof of production conditions and pollution control [125]. Although these fundamental agronomic and safety factors are shared by IBI, EBC and the other schemes mentioned above, their particular thresholds and documentation requirements are not entirely harmonized and the literature currently in publication lacks a systemic comparison across schemes.

Despite these commonalities, neither standard is legally required and regional standards are inconsistent, which leaves investors, regulators and end users in the dark [126]. This lack of standardization is seen as a major obstacle to the expansion of the biochar business and its broader acceptance in agriculture and other industries [122]. It also leads to extremely variable product performance and makes it difficult to compare across field investigations. This ambiguity would be decreased, industrial investment would be stimulated and wider adoption of biochar technology would be supported by creating globally standardized quality classes based on IBI/EBC-type criteria and incorporating them into fertilizer and carbon-credit regulation [126].

8.5. Challenges and future perspectives

The efficacy of biochar is primarily dictated by the type of feedstock and pyrolysis conditions, which influence its chemical composition and soi interactions; due to the varying responses of different crops and soils to biochar application, site-specific assessments are essential prior to making generalized recommendations [127]. Fig. 7 delineates the principal obstacles hindering extensive biochar application, encompassing inconsistent efficacy, pollutant hazards, nutrient and pH discrepancies and ambiguity over long-term stability and expenses. The concerns regarding variable efficacy, contaminant risk, pH imbalance, production and application costs, nutrient imbalances, effects on soil biota and uncertainty regarding long-term environmental impact are contingent upon dosage, feedstock and conditions, rather than being

Fig. 7. Major limitations associated with biochar application in soil systems.

inherent characteristics of biochar. This underscores that responsible large-scale implementation necessitates aligning production and application parameters with the specific soil and cropping systems [73]. Considering the aforementioned restrictions, three research goals would most effectively enhance biochar's preparedness for extensive agricultural application. Initially, extensive multi-year, multi-region field trials are essential to determine how the advantages and dangers of biochar vary with soil type and climatic conditions over time, as the majority of existing research is derived from short-term pot experiments and single-season field studies. Secondly, the standardized documentation of feedstock attributes, pyrolysis parameters and application rates, in conjunction with soil and yield results, would facilitate direct comparisons of the dose-dependent effects outlined in Section 8.2 across studies, rather than relying on qualitative assessments as necessitated by this review. Third, economic feasibility studies, encompassing feedstock and pyrolysis expenses, break-even timelines in relation to yield advantages and field application logistics are essential to ascertain the conditions under which biochar adoption is commercially viable for farmers, directly addressing the adoption gap.

9. Conclusion

Biochar has made essential development in lowering greenhouse gas emissions, and reducing soil nutrient strains, sequestering atmospheric carbon into the soil, and increasing agricultural output. Its role in environmental management has gained close attention due to its physicochemical and biological properties. Biochar marks an eco-friendly, easy, cost-effective technique, whose substrate material is organic waste that is pyrolyzed into the carbon-rich compound. Biochar's high carbon content and residence time in soil are responsible for the improvement in soil fertility due to its sequestered carbon and mineral composition. Moreover, its application has shown effectiveness for diminishing biotic and abiotic stresses in plants. Additionally, the latest developments in nanotechnology for the adaptation of biochar physicochemical properties have gained more attention from researchers due to its enhanced traits for detoxification of soil and wastewater compared to normal biochar. In-depth field research, process and parameters of pyrolysis mechanisms, and the components of the feedstock material, all should be analyzed. Therefore, biochar became an encouraging tool for waste management. Engineered biochar has been broadly used for various environmental applications, like soil fertilizers started a new venture in the improvement of soil quality.

CRediT authorship contribution statement

M. Kamaraj: Writing – review & editing, Validation, Supervision, Project administration, Methodology, Funding acquisition. **Nithya T. G. S:** Writing – review & editing, Validation, Project administration, Methodology. **A. Saranya:** Writing – original draft, Investigation, Formal analysis, Data curation, Conceptualization. **Anu Thomas:** Writing – original draft, Investigation, Formal analysis, Data curation, Conceptualization.

Ethical approval

Not Applicable.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the author(s) used Claude (Anthropic) for language editing during manuscript revision. No AI tools were used in the preparation, generation, or editing of figures or images in this manuscript. After using this tool, the author(s) reviewed, verified, and edited all content, and take responsibility for the content of the published article.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Not Applicable

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