Islam and Xia *Biochar (2026)8:71*
https://doi.org/10.1007/s42773-026-00580-5

Biochar

REVIEW | Open Access

Biochar–soil–tea nexus: a review of soil health, microbial interactions, and sustainable *Camellia sinensis* cultivation

Md Shafiqul Islam[1,2*] and Shangwen Xia[1,2*]

Abstract

Tea (*Camellia sinensis*) cultivation, central to global agriculture and livelihoods, is increasingly challenged by soil degradation, heavy metal contamination, and climate stressors largely driven by intensive practices. Because tea agroecosystems typically occupy acidic, nutrient-poor soils, sustainable management is essential. Biochar, a carbon (C)-rich product of biomass pyrolysis, has emerged as a promising amendment to restore soil health, mitigate contaminants, and strengthen crop resilience. This review synthesizes recent advances on the biochar–soil–tea nexus across five dimensions: (i) soil physicochemical and structural properties, (ii) microbial diversity and functions, (iii) nutrient mobilization and efficiency, (iv) tea productivity and quality, and (v) heavy-metal detoxification. Evidence from field and controlled studies shows that biochar can buffer soil acidity, enhance nutrient retention, restructure microbial communities, reduce pollutant bioavailability, and improve tea growth and quality. In addition, it offers a practice guide for tailoring biochar application based on feedstock and pyrolysis conditions to achieve specific soil and plant health goals. Furthermore, biochar contributes to C sequestration and greenhouse gas mitigation, situating its use within the broader framework of climate-smart agriculture. Despite these benefits, outcomes are highly context-dependent, shaped by feedstock type, pyrolysis conditions, soil characteristics, and application rate. Critical research gaps remain, including scarce tropical field studies, limited long-term field evaluations, inconsistent biochar characterization, and insufficient understanding of cultivar-specific and microbial interactions. By mapping these uncertainties and outlining research priorities, this review provides a foundation for optimizing biochar use in tea systems and guiding region-specific strategies for sustainable cultivation in a changing climate.

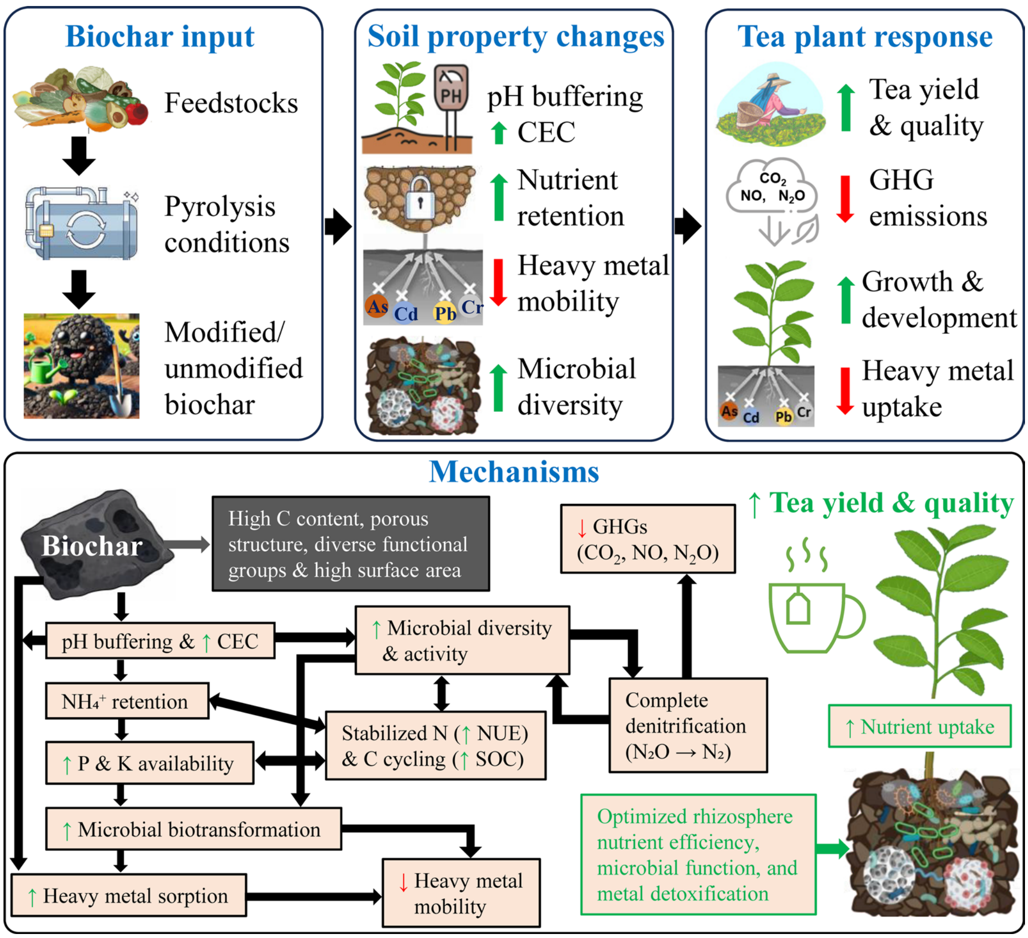
Highlights

- Biochar restores soil health, boosts tea yield and quality, and enhances resilience in sustainable farming.
- Biochar captures carbon, reduces greenhouse gases, and advances climate-smart, eco-friendly tea cultivation.
- Biochar lowers toxic metals in tea, while practical guidance supports safe use and future research needs.

Keywords Soil acidification, Microbial dynamics, Nutrient use efficiency (NUE), Heavy metal immobilization, Functional soil enzymes, Carbon sequestration

*Correspondence:
Md Shafiqul Islam
msislamdebd@yahoo.com
Shangwen Xia
xsw@xtbg.org.cn
Full list of author information is available at the end of the article

Graphical Abstract



1 Introduction

Tea (*Camellia sinensis*) is one of the most economically significant non-alcoholic beverages worldwide, underpinning the livelihoods of millions across Asia, Africa, and Latin America. Beyond its role as a critical cash crop, it remains a cultural staple in regions such as China, India, Sri Lanka, Kenya, and Japan. However, rising global demand has intensified cultivation practices, which often depend on synthetic fertilizers and long-term monocropping, particularly on acidic, nutrient-poor soils (Ghorbani et al. 2024; Liu et al. 2023a, 2023b; Rebello et al. 2022; Yi et al. 2022). Such intensive management has accelerated soil acidification, nutrient imbalance, heavy metal accumulation, and microbial community disruption (Han et al. 2023a, b; Li et al. 2018; Wang et al. 2018a, b). Soil acidification in tea plantations is primarily driven by the long-term use of ammonium (NH_4^+)-based fertilizers, which release protons during nitrification; leaching of base cations such as calcium (Ca^{2+}), magnesium (Mg^{2+}), and potassium (K^+); accumulation of exchangeable aluminum (Al^{3+}) and manganese (Mn^{2+}); and the buildup of organic acids from root exudates and litter decomposition, all of which contribute to nutrient imbalance, metal mobilization, and shifts in soil microbial communities (Li et al. 2018; Liu et al. 2023b; Rebello et al. 2022; Wang et al. 2018a). When combined with climate-induced stresses, these challenges threaten both the productivity and sustainability of tea cultivation. For instance, soil acidification enhances the mobility of toxic metals such as arsenic (As), cadmium (Cd), and lead (Pb), thereby reducing plant vigor and raising concerns about food safety (Borgohain et al. 2022; Chen et al. 2022b; Liu et al. 2023b; Luo et al. 2025; Yi et al. 2022). However, when strongly alkaline amendments such as biochar are applied to correct acidity, transient mobilization of exchangeable Al^{3+} may occur due to changes in complexation equilibria and hydroxide formation. Nevertheless, biochar's high surface area and abundance of oxygen-containing functional groups facilitate Al^{3+} adsorption and precipitation as Al-hydroxides, effectively lowering soluble Al fractions and alleviating toxicity to tea roots (Ji et al. 2020b; Li et al. 2024b; Wang et al. 2018b; Yan et al. 2021). This buffering action stabilizes both pH and metal speciation, thereby minimizing potential risks while restoring soil health. Consequently, there is an urgent need for sustainable soil management strategies that can restore ecological balance without compromising yield.

Biochar, a stable carbon (C)-rich material produced through biomass pyrolysis under limited oxygen conditions, has gained increasing attention as a potential solution. Its high surface area, porosity, aromaticity, and CEC enable improvements in soil properties while serving as a long-term C sink (Min et al. 2022; Zhang et al. 2023, 2024). Various agricultural residues including tea pruning litter, tea waste, rice husk, corn stover, and bamboo have been effectively converted into biochar, underscoring its adaptability to local contexts (Guo et al. 2020; Islam et al. 2023; Li et al. 2021b). Beyond its C stability, biochar can immobilize heavy metals, buffer soil acidity, influence microbial activity, and improve nutrient cycling, making it a promising amendment for degraded soils. Numerous field and laboratory studies have demonstrated its efficacy in enhancing soil fertility in acidic and contaminated environments, with reported increases in soil pH, organic matter content, nutrient retention, and microbial diversity (Ji et al. 2020b; Wang et al. 2023b; Zhang et al. 2024). In tea plantations, biochar application has also been shown to reduce nitrous oxide (N_2O) and nitric oxide (NO) emissions, lower heavy metal bioavailability, and stimulate beneficial microbial functions such as denitrification and C cycling (Han et al. 2023a; Ji et al. 2020a; Zhao et al. 2022). Collectively, these findings highlight biochar's potential as a cornerstone of climate-smart tea agriculture.

Despite its promise, the specific interactions between biochar and tea agroecosystems remain underexplored. This review therefore focuses on the biochar–soil–tea nexus, aiming to elucidate the multifaceted roles of biochar in soil health restoration, plant productivity, microbial dynamics, and environmental resilience within *Camellia sinensis* cultivation. By integrating evidence across disciplines, it seeks to bridge knowledge gaps and synthesize biochar's performance under both field and controlled conditions. Nonetheless, challenges persist, including limited data on long-term field-scale impacts, variability in performance due to feedstock and pyrolysis conditions, and insufficient integration with other organic or biological amendments (Islam et al. 2024; Liu et al. 2023b; Min et al. 2022). Microbial responses in biochar-amended tea soils are also poorly characterized, particularly under diverse climatic and edaphic conditions, and thus warrant further investigation. Although tea is cultivated worldwide, our review reveals a pronounced geographical bias in published biochar–tea research. An extended Web of Science search covering major tropical tea-producing countries (Kenya, Sri Lanka, Vietnam, Indonesia, India, Bangladesh, Myanmar, Uganda, Rwanda, Tanzania, and Malawi) identified no field trials assessing biochar application in tea plantations. This focus on tropical regions was intentional, as subtropical producers such as China, Japan, and Taiwan are already well represented in the literature. The absence of tropical field evidence was consistent across all retrieved studies, including those from Sri Lanka, where research has largely emphasized pyrolysis optimization of tea-waste biochar rather than agronomic field evaluation. This gap represents a significant limitation in the global evidence base, as tropical tea systems are characterized by persistent soil acidity, high rainfall-driven nutrient leaching, and rapid organic matter turnover that differ markedly from temperate and subtropical environments. Consequently, biochar benefits observed in non-tropical systems cannot be assumed to translate directly to tropical tea estates. Well-designed, long-term field trials in major tropical tea-growing regions are therefore urgently needed to evaluate soil fertility, tea yield and quality, climate resilience, and C sequestration under region-specific conditions.

To address these gaps, this review comprehensively explores the role of biochar in tea agroecosystems through a systematic literature search in the Web of Science Core Collection (search strategy, inclusion criteria, and screening process; see S1; Table S1; Fig. S1). Five interrelated dimensions are emphasized. First, biochar's influence on soil properties, including pH buffering, CEC, structure, and organic matter stabilization. Second, effects on soil microbial communities, highlighting diversity shifts, functional gene abundance, and processes such as nitrogen (N) and C cycling. Third, impacts on nutrient dynamics, with focus on phosphorus (P) and K availability and synergies with PGPR and mineral amendments. Fourth, its role in enhancing *Camellia sinensis* productivity and quality indicators such as yield, biomass, polyphenols, amino acids, and caffeine. Finally, biochar's contribution to pollution mitigation and environmental resilience, particularly immobilization of toxic metals like Pb, Cd, chromium (Cr), As, safeguarding plant health, food safety, and contributing to climate change mitigation through GHG reduction and C sequestration. Together, these dimensions provide an integrated framework for understanding biochar's role in sustainable tea cultivation systems.

2 Effects of biochar on soil properties in tea agroecosystems

2.1 Physical improvements: porosity, bulk density, and water retention

Biochar application has demonstrated notable improvements in physical soil properties in tea agroecosystems. Specifically, biochar amendments reduce bulk density and enhance porosity, thereby improving root penetration and aeration. For example, Zou et al. (2023) showed that biochar treatments significantly enhanced soil porosity and structure, which facilitates root proliferation (Zou et al. 2023). Additionally, biochar improved water retention, a critical trait for water-limited environments commonly found in tea-growing regions. Similarly, enhanced soil water holding capacity was indirectly inferred through reduced leachate volume in highly acidic tea soils, confirming better water retention capabilities (Wang et al. 2015). The improved porosity, alongside the high internal surface area of biochar, aids in moisture retention, buffering against drought stress and promoting stable root zone hydration. This makes biochar particularly valuable in sloped tea plantations prone to runoff.

Structurally, biochar enhances soil aggregation and resistance to erosion, which are vital for maintaining tea productivity on the often-steep terrains of tea plantations. Li et al. (2022) documented that the combination of chicken manure and biochar (CMB treatment) promoted the formation of macroaggregates and microaggregates in tea soils, although with varying stability. Improved aggregation contributes to better water infiltration and lower runoff, effectively enhancing erosion resistance. Moreover, biochar-induced aggregation is closely tied to increased microbial activity and the production of extracellular polymers, which act as binding agents in soil aggregate formation. Enhanced aggregate stability was also associated with increased organic matter and C sequestration, especially under treatments that used biochar in combination with organic fertilizers (Han et al. 2022a).

2.2 Chemical changes: pH buffering, cation exchange capacity, and organic matter

Biochar significantly modifies the chemical characteristics of tea-growing soils, with one of its most immediate effects being the reduction of soil acidity. Numerous studies show that biochar application consistently raises soil pH in acidified tea plantations (Liu et al. 2023b; Wang et al. 2015; Yan et al. 2021). This pH-buffering effect is mainly attributed to the alkaline nature and liming capacity of biochar, particularly when produced from high-Ca feedstocks or at high pyrolysis temperatures (Yang et al. 2024). By moderating acidity, biochar stabilizes the chemical environment of strongly weathered, low-pH tea soils. Biochar application also enhances CEC, increasing the retention of essential nutrient cations and reducing leaching losses (Sipayung et al. 2022; Zou et al. 2023). For example, Wang et al. (2018b) reported increased exchangeable Ca^{2+} and decreased exchangeable Al^{3+} following biochar amendment, reflecting improved cation retention and reduced soil acidity. In addition, biochar influences SOM dynamics through its C-rich, aromatic structure, which promotes C stabilization and increases SOM content. Several studies report enhanced microbial biomass and C retention after biochar incorporation, alongside reduced mineralization of native SOM, indicating protection of existing organic matter pools and contributions to long-term C sequestration (Liyanage et al. 2021; Sun et al. 2017). Collectively, these chemical improvements—pH buffering, increased CEC, and SOM stabilization—support the restoration and maintenance of soil fertility in acidified tea agroecosystems.

2.3 Carbon sequestration and climate resilience

Biochar's role in C sequestration is fundamentally attributed to its chemically stable structure and resistance to microbial degradation (Sun et al. 2017; Liyanage et al. 2021). Unlike fresh organic matter, biochar is rich in aromatic C structures formed during pyrolysis, making it highly recalcitrant (Zeng et al. 2022; Chen et al. 2024). This recalcitrant nature enables long-term persistence in soils, contributing significantly to the formation of stable C pools (Han et al. 2023b; Sun et al. 2017; Liyanage et al. 2021). For instance, biochar derived from tea residues significantly enhanced the total organic C content in various soil types, with particularly notable improvements in yellow soils of tea gardens, which experienced up to a 22.84% increase in potentially mineralizable C at a 0.5% application rate (Zeng et al. 2022). Similarly, BFs were shown to elevate SOC content by 16.65–25.50% across different temperature regimes in aged tea plantations (Chen et al. 2024). Additionally, while biochar-amended soils demonstrated increased microbial richness, they did not enhance the abundance of C-cycling genes. This suggests that biochar's contribution to C sequestration stems primarily from its stable composition rather than enhanced microbial turnover (Han et al. 2023b).

Comparative studies reveal that C from biochar is significantly more stable than that from conventional organic amendments. In a two-year study in subtropical tea plantations, manure application resulted in a 36% increase in carbon dioxide (CO_2) emissions due to stimulation of the labile C pool and microbial activity (Han et al. 2023b). In contrast, biochar treatments showed negligible increases in soil respiration, underlining their superior C stability (Liyanage et al. 2021; Sun et al. 2017). Moreover, charged biochar and compost improved microbial biomass and enzymatic activity but still maintained a more stable C profile, suggesting that biochar enhances long-term C sequestration despite supporting short-term microbial functions (Liyanage et al. 2021). BF was also found to reduce the temperature sensitivity of SOC mineralization, particularly at higher temperatures, which is a valuable trait for climate-resilient C storage in tea gardens (Chen et al. 2024). These comparative findings are consolidated in Table S2, which summarizes the mechanisms and climate benefits of biochar-mediated C sequestration in tea cultivation.

2.4 Macronutrient mobilization: enhancing nitrogen, phosphorus, and potassium retention and bioavailability

The mobilization and stabilization of macronutrients such as N, P, and K are essential for maintaining soil fertility in acidified tea-growing systems. Biochar enhances the retention and availability of these nutrients by modifying key soil chemical and microbial processes. Specifically, biochar application improves soil pH and increases the availability of nutrient-bearing ions, resulting in higher concentrations of soil-available N, P, and K (Zou et al. 2023). These effects are closely associated with increases in microbial biomass C and related edaphic properties that regulate nutrient cycling. Co-application of biochar with P- and K-bearing minerals and PGPR further enhances nutrient availability by stimulating microbial functional groups and enzymatic activities that transform soil P and K into more accessible forms (Wei et al. 2025). In addition, tea-waste-derived biochar exhibits strong adsorption capacity for NH_4^+–N, reducing N leaching and improving nutrient retention (Qian et al. 2023). Collectively, these mechanisms promote macronutrient stabilization, reduce environmental nutrient losses, and strengthen the long-term fertility and resilience of acidified tea agroecosystems.

2.5 Micronutrient behavior: altering the solubility and plant uptake of zinc, iron, manganese, magnesium, and calcium

The behavior of micronutrients such as zinc (Zn), iron (Fe), Mn, Mg, and Ca in acidic tea soils is strongly influenced by biochar chemical properties, including pH-buffering capacity, ash content, and feedstock-derived minerals. By increasing soil pH and supplying alkaline cations, biochar can enhance the solubility and availability of selected micronutrients; for example, homogenized biochar significantly increased soil Ca^{2+} and Mg^{2+} concentrations, contributing to improved tea growth (Zou et al. 2023, 2021), and tea-waste biochar similarly elevated exchangeable Ca and Mg pools. However, pH-induced shifts in metal speciation may reduce the availability of some micronutrients, as shown by decreased Mn and Cu uptake following biochar application due to precipitation or stronger adsorption at higher pH (Yan et al. 2021). Feedstock-specific modifications further regulate micronutrient dynamics, with Mg-modified biochar increasing soil Mg^{2+} availability by 519% and improving plant nutrient uptake (Liu et al. 2025). In addition, biochar enhances microbial biomass and enzymatic activity that promote micronutrient mineralization, while integrated nutrient management strategies such as combining biochar with rapeseed cake or inorganic fertilizers have been shown to increase Zn, Fe, Mn, Mg, and Ca availability by improving soil structure and microbial solubilization processes (Manzoor et al. 2024). Collectively, these findings demonstrate that biochar regulates micronutrient behavior through feedstock-dependent mineral inputs, pH-mediated solubility changes, and biologically driven transformation pathways in tea agroecosystems.

Despite strong evidence that biochar improves soil physical structure, pH buffering, CEC, and nutrient retention in tea-growing soils, key uncertainties remain regarding the mechanistic integration and long-term persistence of these effects. Most available studies are short-term and site-specific, limiting understanding of how biochar-driven improvements in aggregation, porosity, and water-holding capacity are sustained under multi-season field management. In addition, the coupled responses of macronutrients (N, P, K) and micronutrients (e.g., Mn, Cu, Zn, Mg) to biochar-induced changes in soil chemistry remain insufficiently resolved, particularly across contrasting soil types and acidification intensities. The extent to which feedstock characteristics, pyrolysis conditions, and application rates regulate micronutrient solubility and plant availability also remains unclear. Long-term, multi-site field experiments are therefore needed to quantify persistence, context dependency, and trade-offs, and to support site-specific biochar application guidelines for sustainable tea agroecosystem management.

3 Biochar–microbe interactions: a key to soil resilience

3.1 Mycorrhizal symbiosis

Although specific investigations on AMF responses to biochar in tea plantations are limited, multiple mechanistic pathways suggest that biochar may enhance AMF colonization in tea roots. Biochar improves soil physicochemical conditions particularly by increasing pH, reducing Al toxicity, and elevating available P and K, thereby creating a less acidic and more nutrient-balanced rhizosphere that supports AMF establishment (Li et al. 2018; Wei et al. 2025). Biochar also enhances microbial biomass, enzymatic activity, and root-zone C availability, which together stimulate AMF propagule germination and hyphal growth through improved habitat quality and energy supply for symbionts. Additionally, biochar's porous structure provides physical microsites that can protect AMF spores and hyphae from desiccation and heavy metal stress factors, especially relevant in acidic, metal-sensitive tea soils. Co-application strategies using biochar with phosphate-solubilizing PGPR and mineral amendments further increase P mobilization, reducing P limitation and promoting AMF symbiotic functioning (Wei et al. 2025). While these mechanisms collectively indicate strong potential for biochar to enhance AMF colonization and symbiotic efficiency in tea systems, comprehensive field studies directly quantifying AMF abundance and functionality under biochar amendments remain limited and represent a key research gap.

3.2 Microbial diversity and structure

Biochar amendments substantially reshape microbial diversity and community structure in tea plantation soils by altering rhizosphere pH, nutrient availability, and habitat conditions. These responses reflect contrasting microbial life-history strategies. Copiotrophic taxa such as Proteobacteria, Actinobacteria, and Firmicutes thrive under nutrient-enriched, C-available conditions due to their rapid growth and metabolic versatility. Biochar particularly when co-applied with organic or mineral fertilizers raises soil pH, enhances nutrient retention and dissolved organic C, and provides porous microhabitats, thereby favoring these groups (Li et al. 2018; Zhang et al. 2025b). In contrast, Acidobacteria, which dominate highly acidic, oligotrophic tea soils and are adapted to low-nutrient conditions, typically decline following biochar-induced pH buffering and nutrient enrichment. Across tea plantations, biochar application consistently increases bacterial richness (Shannon and Chao1 indices), enriches Proteobacteria, Actinobacteria, and Firmicutes, reduces Acidobacteria, and alters fungal assemblages such as Ascomycota and Mortierellomycota (Han et al. 2022b, 2023b; Luo et al. 2023; Yang et al. 2021; Zhang et al. 2023, 2024). Functional analyses using phospholipid fatty acid and Biolog EcoPlate further reveal increased abundances of metabolically active groups including Actinobacteria, Pseudomonas, and Bacillus following biochar and manure application (Li et al. 2018). Collectively, these shifts indicate that biochar drives tea rhizosphere communities from oligotrophic, Acidobacteria-dominated assemblages toward copiotrophic, functionally dynamic microbial networks, enhancing nutrient turnover, soil resilience, and tea productivity.

3.3 Functional genes and biomarkers

Biochar-induced shifts in microbial community structure directly regulate functional gene profiles and biogeochemical processes in tea soils. By enriching copiotrophic, metabolically versatile taxa such as Proteobacteria and Actinobacteria, biochar increases the abundance of key N-cycling genes, including ammonia monooxygenase (*amoA*), nitrite reductases (*nirK*, *nirS*), and N_2O reductase (*nosZ*), reflecting the capacity of these groups to rapidly exploit biochar-enhanced C and nutrient substrates (Ji et al. 2020a, 2022; Han et al. 2023b). Elevated *nosZ* abundance indicates enhanced potential for complete denitrification and reduced N_2O emissions. Concurrent declines in oligotrophic Acidobacteria reduce competition for NH_4^+ and organic N, further accelerating N turnover. Biochar also alters C cycling by reducing cellulose-degrading genes (*cbhI*, GH48) and β-glucosidase activity, as its aromatic structure and sorptive surfaces limit substrate accessibility and favor taxa less specialized in rapid cellulose decomposition (Zhang et al. 2025b; Jiang et al. 2021). Network analyses further highlight strengthened roles of Gemmatimonadetes and Actinobacteria in C-cycling modules under biochar amendment (Han et al. 2022a, 2023b). In addition, biochar enhances microbial necromass accumulation and MCP processes, promoting long-term soil C sequestration through the formation of chemically recalcitrant residues (Shu et al. 2025; Liyanage et al. 2021). Collectively, these findings demonstrate that biochar restructures functional gene networks by shifting microbial life-history strategies, substrate availability, and enzyme expression rather than simply increasing microbial abundance.

3.4 Soil ecosystem functions

Biochar enhances soil ecosystem functioning by modifying the physicochemical environment and restructuring microbial communities, thereby regulating respiration, enzyme activities, and nutrient cycling in tea soils. By increasing soil pH, improving CEC, and providing stable C surfaces, biochar creates favorable conditions for copiotrophic and functionally active microbes, which stimulate key enzymatic activities such as catalase, phosphatase, and sucrase that regulate nutrient mineralization and oxidative detoxification (Han et al. 2022b; Jiang et al. 2021; Zhang et al. 2024; Zheng et al. 2019). These responses collectively enhance soil multifunctionality, enabling the simultaneous operation of multiple ecological processes. Biochar's porous and sorptive structure further modulates C turnover by physically protecting organic substrates, limiting labile C accessibility, and suppressing hydrolytic enzyme expression, resulting in reduced rapid C mineralization despite increased microbial biomass (Zhang et al. 2025b). This shift toward slower decomposition promotes microbial necromass accumulation and strengthens MCP efficiency, supporting long-term soil C sequestration under biochar-amended fertilization regimes (Shu et al. 2025). Together, these mechanisms demonstrate that biochar improves overall soil ecosystem functioning by stabilizing C, enhancing nutrient cycling, and reinforcing microbial networks that support resilience in tea agroecosystems. Biochar–microbe–soil interactions underlying these processes are summarized in Table S3 and illustrated in Fig. 1.

Although increasing evidence shows that biochar reshapes microbial diversity, functional gene expression, and ecosystem processes in tea soils, key uncertainties remain regarding the specificity and durability of these responses. In particular, the effects of biochar on AMF colonization and function in *Camellia sinensis* have rarely been quantified directly and are largely inferred from indirect soil improvements or studies in other cropping systems. The long-term stability of biochar-induced shifts in microbial community composition, functional genes, and enzyme networks under realistic tea management practices and climatic variability is also poorly constrained. In addition, how biochar feedstock characteristics, modification strategies, and application rates regulate microbial life-history strategies, C stabilization pathways, and soil multifunctionality remains insufficiently resolved. Targeted, long-term field studies are therefore needed to define biochar-based microbial management strategies for sustainable tea agroecosystems.

4 Fueling productivity: biochar's role in tea growth and yield

4.1 Boosting nutrient use efficiency: mechanisms in the rhizosphere

Enhancing NUE is critical for sustainable tea production, particularly in acidic soils prone to nutrient loss and inefficient root uptake. Biochar improves NUE through combined rhizosphere physicochemical modifications and microbially mediated nutrient transformations. The co-application of rapeseed cake with biochar and mineral fertilizers significantly increases nutrient uptake per unit root length, surface area, and volume by improving soil pH, CEC, and root absorptive capacity (Manzoor et al. 2022). Biochar's porous, surface-charged structure enhances rhizospheric nutrient retention, reduces NH_4^+ and nitrate (NO_3^-) leaching, and promotes fine-root proliferation, thereby strengthening root–soil nutrient exchange. Evidence from a 15N isotope tracing study further shows that biochar combined with N-fertilizer increases plant N uptake while reducing gaseous N losses by suppressing ammonia volatilization and lowering N_2O emissions through enhanced regulation of nitrification and denitrification pathways (Wang et al. 2018a). In addition, the combined application of pruned tea litter and biochar increases NH_4^+–N availability by 1.7–9.5 times and restructures microbial communities by enriching Ascomycota and other nutrient-mobilizing fungi positively correlated with available N pools (Luo et al. 2023). These microbial shifts enhance ammonification and mineralization processes, improving the conversion of organic N to plant-available forms. Collectively, these rhizosphere-level mechanisms explain how biochar substantially enhances NUE in tea agroecosystems.

4.2 Physiological and morphological parameters

Biochar enhances the physiological and morphological performance of *Camellia sinensis* by improving soil chemical balance, nutrient bioavailability, and rhizosphere biological activity, thereby promoting leaf expansion, biomass accumulation, and photosynthetic efficiency. In acidic tea soils, biochar-mediated increases in soil pH, available P, K, and Mg, together with reduced Al toxicity, create a more favorable environment for shoot and root development. For example, bamboo- and rice-derived biochars applied at 2.5–5% (w/w) significantly increased aboveground biomass and leaf area, closely associated with higher foliar P, K, and Mg concentrations and enhanced photosynthetic rates (Yan et al. 2021). These responses align with biochar-induced stimulation of microbial activity, nutrient cycling, and rhizosphere enzyme function, which increase the supply of plant-available nutrients and support C assimilation (Sects. 3.1–3.4). However, excessive application rates can diminish benefits; very high doses (e.g., 64 t ha^{-1}) have been shown to induce nutrient immobilization and micronutrient deficiencies, particularly Mn and Cu, due to strong pH-driven reductions in solubility (Wang et al. 2015; Yan et al. 2021). Soil type further modulates responses, with improved plant performance in yellow soils but reduced benefits in purple and paddy soils under high biochar inputs (Chen et al. 2022a; Zeng et al. 2022).

Homogenized biochar has also produced substantial gains in plant growth, increasing leaf biomass by 80.9% and root biomass by 262.2%, alongside marked increases in N, P, and K uptake (Zou et al. 2023). Root chamber and field studies indicate that biochar-driven increases in microbial biomass C, exchangeable Ca, total N, and SOM stimulate root proliferation and functional root traits, enhancing water and nutrient acquisition (Hu et al. 2024; Zou et al. 2023). Field-scale trials further show that tea-waste biochar increased tea production by 2.3-fold in weaker growth sectors and 1.3-fold in normal sectors,

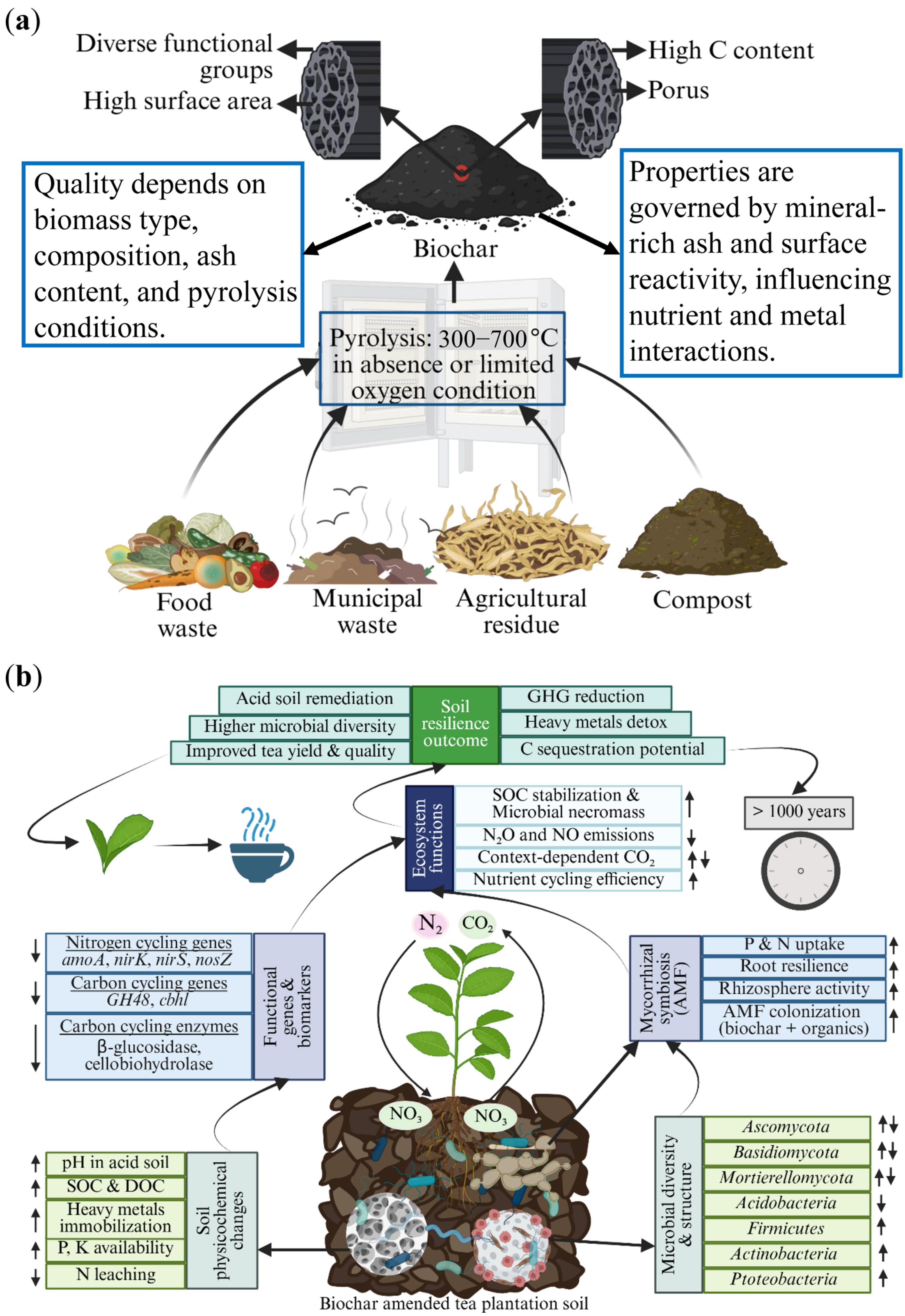


Fig. 1 Biochar production and its characteristics (**a**), and biochar-microbe interactions: A key to soil resilience in tea agroecosystem (**b**)

linked to improved soil electrical conductivity, organic matter, and phosphate availability (Sipayung et al. 2022). Collectively, these findings demonstrate that biochar improves tea plant physiology and morphology through integrated effects on soil chemistry, nutrient dynamics, and rhizosphere functioning, while underscoring the need for soil-specific optimization of application rates to avoid nutrient imbalances.

4.3 Yield improvement and quality

Biochar enhances tea yield and quality through integrated improvements in soil chemistry, microbial functioning, and nutrient dynamics that support both vegetative and reproductive growth. Machine-learning analysis identified soil and biochar Ca content, together with application rate, as key predictors of yield, highlighting the role of Ca in alleviating acidity stress and promoting root development in tea plantations (Yin et al. 2025). By buffering soil pH, increasing CEC, and reducing Al^{3+} toxicity, biochar creates a more favorable rhizosphere for nutrient uptake and shoot formation. Accordingly, BFs, particularly formulations containing ~ 30% biochar, significantly increase bud length, 100-bud weight, and shoot density by enhancing the availability of N, K, and Ca and stimulating nutrient-cycling microbial communities (Yang et al. 2025). Field experiments further show that combining biochar with chemical fertilizers increases tea yield by up to 39.2%, driven by greater shoot biomass and density associated with improved soil fertility and copiotrophic microbial shifts (Yang et al. 2021).

Biochar also improves tea quality by regulating nutrient supply and rhizosphere conditions that control secondary metabolite synthesis. BFs increase free amino acids, flavonoids, and soluble sugars while reducing catechin derivatives such as epigallocatechin gallate, thereby improving sensory balance (Yang et al. 2025). Consistently, biochar application raises the catechin quality index to levels comparable with bio-organic fertilizers, reflecting enhanced soil total N and available K that support polyphenol and amino-acid biosynthesis (Yin et al. 2024). Improved nutrient availability and reduced Al toxicity further enhance root activity, N assimilation, and carbohydrate allocation—key drivers of both yield and quality. Across field studies, biochar application results in 10–20% yield increases and significant improvements in leaf quality in acidified tea soils (Liu et al. 2023b; Li et al. 2024a; Yan et al. 2021; Han et al. 2023b). Collectively, these findings show that biochar strengthens tea productivity and quality by jointly enhancing soil fertility, nutrient-use efficiency, microbial functions, and biochemical pathways underlying flavor and aroma formation. Collectively, these findings demonstrate that biochar strengthens tea productivity and quality by simultaneously improving soil fertility, nutrient uptake efficiency, microbial functional processes, and the biochemical pathways underlying flavor and aroma formation.

Despite substantial evidence that biochar improves NUE, growth, yield, and quality of *Camellia sinensis*, important uncertainties remain regarding the persistence and context dependency of these responses. Most studies are short-term, limiting understanding of how biochar influences seasonal nutrient dynamics, root physiology, and yield stability under long-term field conditions. In addition, interactions between biochar properties, tea cultivar traits, and rhizosphere microbial communities remain poorly resolved, particularly with respect to N assimilation and secondary metabolite synthesis that determine tea quality. The extent to which biochar application rates and modification strategies optimize yield–quality trade-offs across contrasting soils and management regimes also remains unclear. Long-term, cultivar-specific field studies integrating plant physiology and belowground processes are therefore needed.

5 Environmental impacts

5.1 Greenhouse gas mitigation

Biochar applications in tea systems contribute to climate-smart agriculture by lowering GHG emissions and offering potential pathways for C credit generation. Laboratory trials demonstrated that wheat-straw-derived biochar reduced N_2O emissions by up to 94% and lowered the GWP by 33.45% compared to controls (He et al. 2016). Similarly, biochars derived from burcucumber biomass reduced CO_2 and N_2O emissions by 24% and 34%, respectively, during soil incubation (Kim et al. 2015). Life cycle assessments further affirm the C-negative potential of biochar. When biochar produced as a by-product of Arundo donax pyrolysis was applied to soils, the emission reduction reached up to 198.02%, surpassing other processing routes in climate benefits (Zongwei et al. 2025). These features enhance biochar's value as a tool for achieving net-negative emissions in agricultural systems and aligning with C trading mechanisms.

5.2 Heavy metal detox: biochar's role in pollution abatement

5.2.1 Sources of metal pollution in tea systems

Tea plantations are increasingly vulnerable to heavy metal contamination from diverse sources. Fertilizer residues, particularly from excessive use of synthetic N-based fertilizers, contribute significantly to soil acidification, thereby increasing the mobility of toxic metals such as Pb, Cd, and As. In long-term tea cultivation systems, the acidified soils amplify the bioavailability of these contaminants, raising concerns over food safety and ecological risks (Wang et al. 2018b; Yi et al. 2022). Industrial pollution, including mining, smelting, and atmospheric deposition, further exacerbates heavy metal accumulation in tea-producing regions (Luo et al. 2025). Legacy pollution embedded in soils from past land uses remains a persistent source of contamination, particularly in regions with inadequate soil remediation practices.

5.2.2 Biochar's role in remediation

Biochar has demonstrated substantial potential for mitigating heavy metal contamination through mechanisms such as sorption, immobilization, and pH modulation. The effectiveness of biochar in reducing heavy metal mobility and bioavailability has been well-documented across various soil types, including tea-growing regions. Its porous structure and abundance of functional groups particularly in N-doped and magnetically enhanced forms facilitate strong interactions with metal ions like Cd^{2+}, Cu^{2+}, Cr^{6+}, Ni^{2+}, and Pb^{2+} (Guo et al. 2020, 2022; Peng et al. 2024; Saleem et al. 2024). Tea-waste-derived biochars, in particular, offer a sustainable solution, repurposing agricultural waste into high-performance adsorbents. For instance, rose-flower-like magnetic biochars from tea waste showed high sorption capacities for nickel (Ni^{2+}) and cobalt (Co^{2+}) up to 147.84 mg g^{-1} and 160.00 mg g^{-1}, respectively, due to enhanced surface area and magnetically active sites (Shirvanimoghaddam et al. 2021). The immobilization efficiency is also influenced by pyrolysis temperature: higher temperatures typically yield biochars with greater surface area and alkalinity, enhancing their capacity to adsorb metals and raise soil pH (Gotore et al. 2024; Li et al. 2017). Biochar application has also been shown to shift metal speciation in soils from exchangeable or acid-soluble fractions to more stable organic-bound or residual forms, thereby reducing environmental risk (Islam et al. 2024, 2023; Lu et al. 2017).

Molecular-level analyses have clarified the mechanisms through which biochar immobilizes heavy metals in acidic tea plantation soils. X-ray photoelectron spectroscopy and Fourier-transform infrared spectroscopy consistently demonstrate that Pb, Cd, and As form strong associations with oxygen-containing functional groups, including carboxyl (–COOH), hydroxyl (–OH), and carbonyl (C=O) groups on biochar surfaces, resulting in the formation of stable inner-sphere complexes and metal–organic precipitates (Akgül et al. 2019; Liu et al. 2023b; Li et al. 2024a; Han et al. 2023b). Comparisons across biochar types further show that Fe- and Mg-modified biochars provide superior immobilization capacity relative to unmodified materials. Fe-modified biochar enhances Pb^{2+} and As(V) sequestration through Fe–O–metal bridging and the formation of Fe–As co-precipitates, whereas Mg-modified biochar more effectively stabilizes Cd^{2+} via surface complexation, cation exchange with Mg^{2+}, and the precipitation of Cd–Mg carbonates. Evidence from acidic soil systems, including tea-growing and related agroecosystems, indicates that scanning electron microscopy–energy-dispersive X-ray spectroscopy analyses frequently detect Pb–O, Cd–O, and As–Fe precipitates on modified biochar surfaces, supporting the plausibility of long-term stabilization pathways under low-pH field conditions (Islam et al. 2024; Yan et al. 2021). Nevertheless, most of these mechanistic insights originate from controlled laboratory studies, and field-scale spectroscopic validation in tea plantation soils remains limited highlighting an important research frontier for advancing biochar-based remediation in *Camellia sinensis* agroecosystems.

5.2.3 Toxicity mitigation: preventing accumulation in edible tea parts

Beyond heavy metal immobilization, biochar amendments have been shown to alleviate fluoride, As, and Cd toxicity while simultaneously enhancing seedling biomass and photosynthetic pigment content, highlighting its dual remediation–nutrition role in supporting plant performance and environmental safety (Islam et al. 2021a; Li et al. 2024a, b; Wang et al. 2023a). One of the most critical aspects of biochar use in tea systems is its ability to prevent the translocation of heavy metals into edible plant parts, particularly leaves and buds, which are directly consumed. In Pb- and Cd-contaminated tea plantations, field trials demonstrated that biochar reduced Pb concentrations in tea leaves by up to 61.28%, significantly lowering human exposure risk (Liu et al. 2023b). The immobilization of metals in the rhizosphere, combined with improved soil nutrient balance, limits the uptake and translocation of contaminants. In addition, modified biochars can alter the subcellular distribution of metals within tea plants, promoting their sequestration in cell walls and vacuoles rather than the cytoplasm, thereby minimizing toxicity and preserving physiological functions (Dong et al. 2025). These effects not only protect plant health but also maintain or even improve tea yield and quality.

Although biochar-induced liming effectively reduces the bioavailability of toxic metals such as Pb, Cd, and As, transient mobilization of certain micronutrients (e.g., Zn, Cu, Ni) can occur immediately after application due to rapid pH shifts and changes in ionic equilibria. These temporary increases in solubility may lead to short-term uptake by plants before metals are immobilized through precipitation, ion exchange, or complexation with biochar's oxygen-containing functional groups and associated mineral phases. Over time, the formation of stable metal–biochar complexes and increased soil pH contribute to a significant decrease in overall metal bioavailability, as observed in tea plantations and other acidified systems (Han et al. 2023b; Islam et al. 2024; Li et al. 2024a; Liu et al. 2023b; Yan et al. 2021).

5.2.4 Tea as a bioindicator: monitoring pollutant dynamics via plant uptake

Tea plants, due to their perennial lifecycle, deep rooting, and sensitivity to environmental changes, serve as effective bioindicators for heavy metal dynamics in soils. The concentration of metals in tea leaves reflects changes in bioavailability and serves as a proxy for the effectiveness of soil remediation strategies. Biochar application, which reduces the exchangeable fraction of metals, consistently results in lower concentrations in plant tissues offering both a protective and diagnostic function (Islam et al. 2021b, 2024). Additionally, biochar's influence on tea plant uptake can guide optimization of remediation strategies. For example, the use of tea-waste biochar at 500–600 °C significantly reduced Cd uptake by altering metal speciation and improving soil pH and organic C content (Li et al. 2017). As such, tea not only benefits from remediation but can also serve as a real-time monitor of soil health and pollutant stabilization. The key pathways and mechanisms of biochar-mediated heavy metal detoxification are summarized for clarity in Fig. 2 and Table S4.

Although biochar has demonstrated potential to reduce GHG emissions and enhance C sequestration in tea agroecosystems, key uncertainties remain regarding the consistency and durability of these effects under field conditions. Most evidence is derived from short-term laboratory or incubation studies, limiting insight into how biochar-mediated N_2O and CO_2 mitigation responds to seasonal variation, soil moisture dynamics, and long-term management practices. In addition, the relative importance of biochar feedstock, pyrolysis temperature, and application rate in regulating emission pathways remains insufficiently quantified in tea systems. Field-scale assessments linking microbial functional genes, gas fluxes, and C stability are therefore needed to validate climate-mitigation benefits across diverse tea-growing environments.

6 Management strategies for sustainable tea cultivation

6.1 Tailoring biochar properties

The performance of biochar in tea plantations is strongly influenced by feedstock type, pyrolysis temperature, and application rate, which together determine its effectiveness in improving soil fertility and mitigating metal

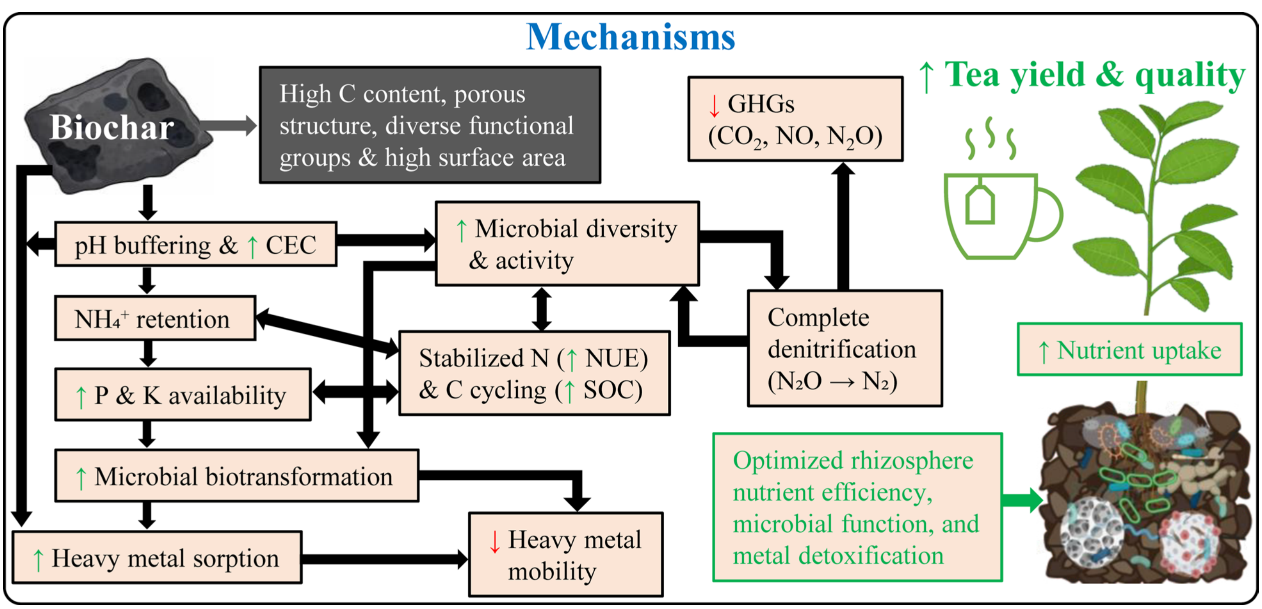


Fig. 2 Integrated mechanism diagram illustrating the interactions between biochar, soil processes, and tea plant responses. Biochar surface functional groups (carboxyl (–COOH), hydroxyl (–OH), and carbonyl (C=O)) and mineral phases (e.g., Fe–O, Mg–O) bind heavy metals such as cadmium (Cd^{2+}), lead (Pb^{2+}), and arsenic (As), reducing their mobility and bioavailability. Biochar pores provide habitats for beneficial soil microorganisms, including Actinobacteria, Proteobacteria, and phosphate-solubilizing taxa, which mediate key transformations of nitrogen (N), phosphorus (P), and potassium (K). These processes collectively enhance nutrient availability and uptake by tea roots, improving plant growth, stress tolerance, and overall tea quality

toxicity. Biochars derived from tea pruning residues or tea-processing waste enhance soil fertility and reduce heavy-metal availability (Borgohain et al. 2022; Sipayung et al. 2022), while bamboo- and rice-husk biochars increase soil P availability and reduce bioavailable Mn and Cu, improving nutrient balance in acidic tea soils (Yan et al. 2021). Pyrolysis temperature governs key functional properties: biochars produced at 500–600 °C exhibit greater aromaticity, surface area, and pH-buffering capacity, enhancing heavy-metal immobilization and soil organic C stabilization (Mayakaduwa et al. 2016; Zhao et al. 2022). Feedstock-specific effects are also evident, with high-ash manure-derived biochars acting as effective liming agents and lignocellulosic biochars produced at ≥600 °C providing stronger metal-binding capacity. Application rate further modulates outcomes; although excessive doses (e.g., 64 t ha^{-1}) may cause diminishing returns or nutrient immobilization (Wang et al. 2015), field evidence suggests that 20–30 t ha^{-1} optimizes soil fertility, N retention, and plant performance (Zhang et al. 2025a). Responses remain soil-specific, as tea-residue biochar enhanced C sequestration in yellow soils but showed reduced effectiveness in purple and paddy soils at higher rates (Zeng et al. 2022), highlighting the need for soil- and cultivar-specific tailoring of biochar properties and application strategies (Table S5). Beyond biophysical considerations, practical deployment is constrained by logistical and economic factors, including the energy-intensive nature of biomass transport and pyrolysis, which increases the cost of centralized production. Although portable pyrolysis units may reduce transport-related emissions, their capacity and cost-effectiveness remain limited (Sahoo et al. 2021). Moreover, optimizing pyrolysis conditions for waste-tea biochar—typically 450–500 °C with 45–60 min residence time—requires technical expertise and infrastructure that are often lacking in tea-growing regions (Amarasinghe et al. 2016). Collectively, these constraints underscore the need for region-specific, scalable, and economically viable biochar production and deployment strategies to support widespread adoption in tea agroecosystems.

6.2 Fertilizer management and nutrient synergy

Integrating biochar with organic and inorganic fertilizers is essential for optimizing NUE in tea agroecosystems. Due to the inherently acidic and leaching-prone nature of tea soils, applied nutrients especially N, P, and K are often lost before plant uptake. Biochar improves nutrient retention by increasing soil pH, enhancing CEC, and reducing acid-driven nutrient losses (Li et al. 2024a; Zhang et al. 2025a). Significant synergy is observed when biochar is combined with organic inputs such as rapeseed cake, compost, or tea pruning litter. Co-application enhances nutrient uptake per unit root length, surface area, and volume by improving rhizospheric N retention and reducing gaseous N losses (Manzoor et al. 2022; Wang et al. 2018b). Tea-waste biochar's high NH_4^+–N adsorption capacity further reduces leaching losses and enhances N availability during critical growth stages (Qian et al. 2023). Biochar also improves P and K dynamics by limiting P fixation through stabilization of Al–Fe–P interactions and enhancing K availability when paired with mineral fertilizers or PGPR inoculants (Wei et al. 2025). These impacts are associated with increases in microbial enzyme activities (acid phosphatase, β-glucosidase) and shifts in functional genes linked to N and P cycling (*amoA*, *nirK*, *nosZ*), as shown in Table S3. Importantly, biochar-based nutrient strategies can partially or fully substitute synthetic fertilizers without compromising yield or leaf quality. Biochar applications extend nutrient availability beyond the 2–4 week window typically observed for mineral fertilizers (Zhang et al. 2025a). When combined with organic fertilizers, they promote long-term nutrient cycling, reduce leaching losses, and lower GHG emissions (Manzoor et al. 2022). These findings support a transition toward integrated nutrient management systems that reduce dependence on chemical inputs while improving soil health and environmental resilience (Table S6).

6.3 Integrated biochar-based approaches

For long-term sustainability, biochar should be integrated into holistic soil and nutrient management frameworks tailored to specific site conditions. Co-application of biochar with organic fertilizers, microbial inoculants, or mineral supplements enhances soil structure, nutrient cycling, and plant performance. Biochar–organic fertilizer combinations improve soil aggregate stability and SOC retention more effectively than organic fertilizers alone (Wang et al. 2025). Integrated fertilization practices further increase NUE and reduce N losses through ammonia volatilization, NO_3^- leaching, and N_2O emissions (Manzoor et al. 2024; Zheng et al. 2019). Biochar also stabilizes micronutrient dynamics. While biochar elevates Ca and Mg and maintains healthy leaf nutrient levels (Zou et al. 2023; Li et al. 2021a), careful balancing with organic inputs is essential to avoid excessive pH increases that may reduce Mn and Cu availability (Yan et al. 2021). Integrating biochar with organic amendments also decreases the bioavailability of Pb, Cd, Cr, and Ni in acidified tea soils while sustaining tea yield and quality (Table S4). Moreover, integrated biochar management contributes to climate resilience by stabilizing SOC, reducing GHG emissions, and promoting microbial necromass accumulation (Liyanage et al. 2021; Han et al. 2023b).

6.4 Dose response patterns and rate-effect curves in tea agroecosystems

Biochar exhibits a nonlinear dose–response pattern in tea agroecosystems, with soil properties, microbial communities, nutrient dynamics, and plant performance responding differently across application rates. Evidence from field and pot studies shows that low-to-moderate rates (5–10 t ha^{-1}) modestly increase soil pH, reduce Al^{3+} toxicity, improve exchangeable K, and enhance microbial diversity without excessively altering rhizosphere conditions (Han et al. 2022b; Li et al. 2018; Luo et al. 2023). Intermediate rates (15–20 t ha^{-1}) provide the most consistent and integrative benefits, including stronger pH buffering, reduced nutrient leaching, upregulation of key N-cycling genes (*amoA*, *nirK*, *nirS*, *nosZ*), increased microbial network complexity, 10–20% yield improvements, and reduced Cd and Pb accumulation in tea foliage (Ji et al. 2020a, 2020b, 2022; Han et al. 2023b; Borgohain et al. 2022; Liyanage et al. 2021). At higher rates (> 25–30 t ha^{-1}), responses often plateau or become neutral, and in some cases negative effects arise due to overliming, suppressed N mineralization, reductions in Acidobacteria, and dissolved organic carbon-driven shifts in microbial regulation (Li et al. 2018; Lu et al. 2017; Zhang et al. 2023). Optimal biochar rates therefore vary with soil type, biochar feedstock and pyrolysis temperature, fertilizer co-application, and contamination severity; high-temperature woody biochars often perform effectively at 5–10 t ha^{-1}, whereas low-temperature crop-residue and tea-waste biochars may require ≥ 15 t ha^{-1} (Zhang et al. 2025b; Jiang et al. 2021; Dong et al. 2025). Collectively, these findings show that 20 t ha^{-1} is not a universal optimum, but rather lies within a broader functional range of approximately 10–25 t ha^{-1}, reinforcing that biochar application must be tailored to soil conditions, biochar characteristics, and management objectives in tea cultivation (Fig. 3).

While numerous studies confirm that biochar reduces heavy metal mobility and accumulation in tea plants, several critical gaps remain regarding long-term stability and mechanistic specificity. Most existing studies focus on short-term immobilization, leaving uncertainty about the persistence of metal stabilization and potential remobilization under aging biochar and fluctuating soil conditions. In addition, molecular-level mechanisms governing interactions between biochar surface chemistry, rhizosphere microbes, and metal speciation in tea soils remain incompletely resolved. The influence of biochar type, modification strategy, and application rate on

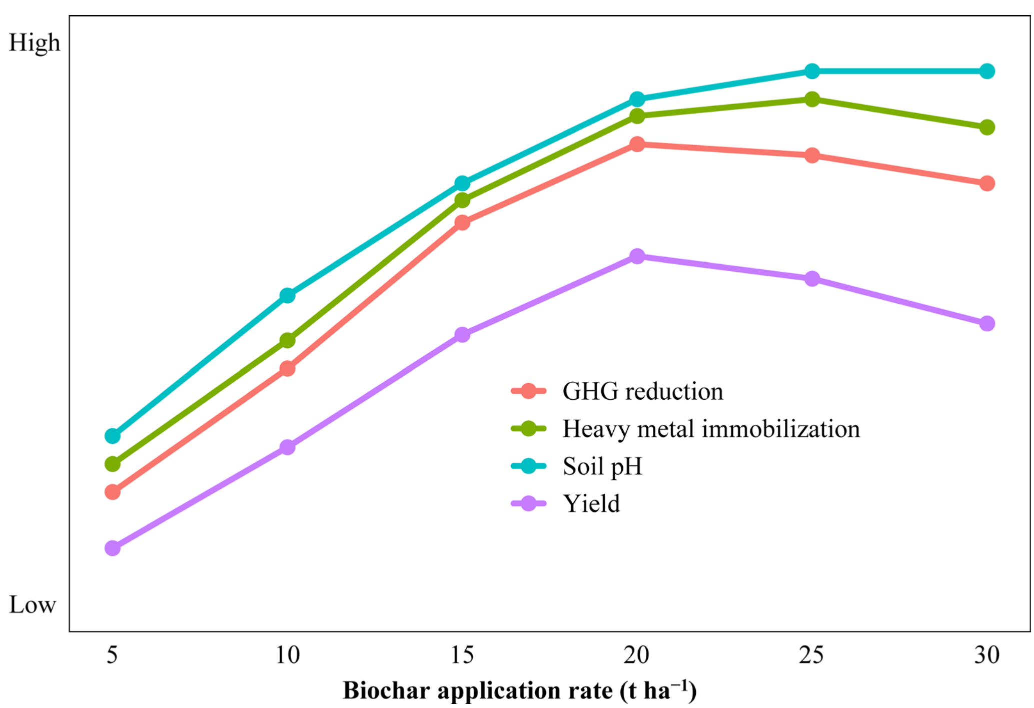


Fig. 3 Conceptual dose–response curves illustrating generalized nonlinear biochar effects on greenhouse gas (GHG) reduction, heavy metal immobilization, soil pH, and yield, in tea agroecosystems. Curves are synthesized from trends reported across multiple field and pot studies and represent illustrative (non-empirical) patterns. Substantial improvements occur at moderate rates (5–10 t ha^{-1}), peak responses are observed at intermediate rates (15–20 t ha^{-1}), and diminishing or neutral effects follow at higher rates (> 25 t ha^{-1})

metal uptake across different tea cultivars and soil types also requires further clarification. Long-term field studies integrating soil chemistry, plant uptake, and microbial processes are therefore essential.

7 Potential risks and controversies in biochar-based tea management

7.1 Alkaline injury and micronutrient imbalance from high-ash or high-rate biochars

Biochar effectively ameliorates acidic tea soils; however, high-ash biochars or excessively high application rates can induce over-liming, elevating soil pH beyond optimal thresholds for tea. Tea plants are highly pH-sensitive, and even modest over-alkalization can markedly reduce the availability of micronutrients such as Mn, Zn, and Cu. Evidence from bamboo and rice-husk biochar applications demonstrates that although biochar enhances plant biomass, leaf Mn and Cu concentrations decline due to reduced solubility at elevated pH (Yan et al. 2021). Similar micronutrient shifts have been reported for tea-pruning-litter biochar, which alters Cu, Mn, and Zn speciation from exchangeable to more recalcitrant fractions, potentially constraining long-term micronutrient supply (Sarmah et al. 2023). Field evaluations also show that extremely high biochar application rates (e.g., 64 t ha^{-1}) can induce nutrient immobilization and diminish agronomic effectiveness (Wang et al. 2015; Zeng et al. 2022). These findings underscore the necessity of optimizing application rates and monitoring micronutrient dynamics to prevent imbalances that may offset the benefits of soil amelioration.

7.2 Potential presence of polycyclic aromatic hydrocarbons and heavy metals in biochar

Biochar quality is strongly governed by feedstock type and pyrolysis conditions. While most tea studies utilize plant-derived biochars with relatively low contaminant risk, biochars produced from sewage sludge, industrial by-products, or polluted biomass may contain elevated concentrations of heavy metals, PAHs, or other hazardous organics. Min et al. (2022) reported that sewage-sludge-derived biochars can accumulate metals requiring stabilization steps to ensure safe land application. Mohan et al. (2024) further highlight that although biochar can immobilize metals, improperly characterized biochars may introduce new contaminants into soils. Complementary evidence from paddy soil studies indicates that biochar can modify metal speciation and, under certain redox conditions, increase mobility (Islam et al. 2023, 2024; Lu et al. 2017). Although tea-focused biochar research overwhelmingly employs plant-based feedstocks, the manuscript now emphasizes the importance of rigorous feedstock screening, PAH analysis, and contaminant certification prior to field application.

7.3 Stability of nitrous oxide suppression across climates and management regimes

Biochar consistently reduces N_2O emissions in acidic tea soils, largely due to enhanced denitrification and increased *nosZ* gene abundance (Ji et al. 2020a, b, 2022; Wu et al. 2023). Wheat-straw biochar produced N_2O reductions of up to 94% under controlled conditions (He et al. 2016). However, the stability of these reductions across different climatic zones, soil types, and moisture regimes remains uncertain. A synthesis by Han et al. (2023a) demonstrates substantial variability in N_2O responses to soil amendments, with outcomes strongly modulated by soil pH, N form, moisture levels, and seasonal patterns. Furthermore, emerging mechanistic evidence indicates that biochar-derived persistent free radicals and shifts in the balance between *nirK* and *nosZ* functional groups may weaken or even reverse N_2O suppression under certain environmental conditions (Wu et al. 2023). These findings highlight the need for long-term, multi-site experiments to determine the robustness of N_2O mitigation strategies for diverse tea-growing regions.

7.4 Short-term nitrogen immobilization following biochar application

Although biochar enhances N retention and reduces leaching in the long term, its strong sorptive capacity can temporarily immobilize mineral N, limiting availability during early growth stages. Tea-residue-derived biochars, in particular, show high NH_4^+ retention capacity, which improves NUE over time but may constrain early N availability immediately following application (Qian et al. 2023). High application rates intensify this short-term effect, as evidenced by Wang et al. (2015), who found that very high doses decreased agronomic performance due to nutrient immobilization despite reducing N losses. Zhang et al. (2025a) likewise reported that while biochar can prolong soil N supply, benefits plateau or decline when application rates exceed optimal ranges, especially without synchronized N fertilization. To mitigate these transient limitations, the revised manuscript recommends adjusting fertilizer timing and integrating biochar with complementary organic or mineral N sources, aligning with sustainable N management practices in tea systems (Rebello et al. 2022).

Despite growing evidence that tailoring biochar feedstock, pyrolysis conditions, and application rates can optimize benefits in tea agroecosystems, standardized guidelines remain lacking. Most studies evaluate single biochar types or rates, providing limited insight into dose–response relationships and trade-offs such as over-liming, micronutrient imbalance, or nutrient immobilization. In addition, the interactive effects of biochar with organic fertilizers, mineral amendments, or microbial inoculants remain insufficiently tested under field conditions. The scalability and transferability of optimized biochar strategies across soil types, climatic zones, and tea cultivars also remain poorly constrained. Systematic, multi-factor field trials are therefore required to develop robust, site-specific biochar management frameworks.

8 Integrated synthesis

8.1 Mechanisms

Across tea agroecosystems, biochar influences soil, microbial, plant, and environmental processes through a coherent set of mechanisms supported by moderate-to-strong evidence (Table 1). In soil systems, its alkaline pH, high surface area, and CEC buffer acidity, adsorb Al^{3+} and Mn^{2+}, enhance nutrient retention, and stabilize organic C, thereby improving soil structure, porosity, and water-holding capacity in both field and controlled studies. These physicochemical changes reshape rhizosphere microbial communities by shifting oligotrophic, Acidobacteria-dominated assemblages toward copiotrophic groups such as Proteobacteria and Actinobacteria, while increasing enzymatic activities and functional genes (*amoA*, *nirK*/*nirS*, *nosZ*) that strengthen nutrient cycling and long-term C stabilization through MCP pathways. Enhanced root-zone chemistry and microbial functioning translate into plant-level benefits, including reduced Al toxicity, improved nutrient availability, greater nutrient uptake efficiency, enhanced photosynthesis, and increased shoot biomass, collectively contributing to 10–40% yield gains and improved tea quality traits. Environmentally, biochar reduces N_2O and NO emissions—often by 25–94%—by modifying nitrification–denitrification pathways and enriching complete denitrifiers, and it immobilizes toxic metals such as Pb, Cd, Cr, and others through surface complexation, precipitation, and pH-driven speciation changes, thereby lowering their uptake into tea leaves. Together, these integrated mechanisms demonstrate biochar's capacity to restore soil health, strengthen nutrient cycling, enhance plant performance, and mitigate environmental risks in tea cultivation.

8.2 Knowledge gaps

Despite clear benefits, biochar responses in tea agroecosystems remain highly context-dependent, with outcomes varying according to feedstock type, pyrolysis temperature, soil acidity, climate regime, and cultivar, underscoring the need for site-specific application guidelines. A major geographical gap persists: no field-based biochar studies have been conducted in key tropical tea-producing regions such as Kenya, Sri Lanka, Vietnam, and Indonesia, where high rainfall, strong acidity, and rapid organic-matter turnover may alter biochar behavior and limit the transferability of findings from subtropical systems. Additional uncertainties include the risk of micronutrient imbalances from high-ash biochars, potential contaminant introduction from poorly characterized feedstocks, short-term N immobilization, and variable N_2O mitigation outcomes driven by soil and environmental conditions.

9 Research priorities

Advancing biochar-centered management in tea cultivation will require long-term, multi-factor field experiments that reflect the diversity of global tea-growing environments. Priority should be given to factorial trials integrating biochar type (e.g., woody, crop-residue, modified) × application rate (e.g., low, moderate, high) × tea cultivar (e.g., China: 'Fuding Dabaicha', 'Yunkang 10'; Sri Lanka: TRI 2025; Kenya: TRFK 6/8) × region (e.g., subtropical China, tropical Sri Lanka, East African highlands). Such studies should run for at least five years, with quarterly sampling during the first three years and biannual sampling thereafter to capture seasonal dynamics, stabilization pathways, and long-term soil–plant–microbe interactions. Key evaluation metrics include SOC fractions (permanganate-oxidizable carbon, mineral-associated organic carbon), microbial community profiling (16S ribosomal ribonucleic acid, internal transcribed spacer, functional genes), nutrient cycling indicators, metal speciation (e.g., Community Bureau of Reference extraction), and comprehensive assessments of tea quality (catechins, amino acids, polyphenols, sensory attributes). Closing major geographic gaps—especially in tropical systems—is essential for producing globally relevant recommendations, while coordinated standards for biochar characterization, quality assurance (including PAH and heavy-metal screening), and risk monitoring will enhance reproducibility and environmental safety. Collectively, these research priorities provide a clear roadmap for developing site-specific, climate-smart, and scalable biochar strategies that can improve soil fertility, plant productivity, and environmental resilience in tea agroecosystems.

10 Conclusion

Biochar holds significant promise for enhancing the sustainability, resilience, and productivity of tea agroecosystems. Evidence synthesized across soil, plant, microbial, and environmental dimensions demonstrates that biochar can effectively ameliorate soil acidity, improve nutrient availability, enhance microbial community structure

Table 1 Integrated summary of biochar effects in tea agroecosystems

Theme	Key findings	Mechanisms/processes	References
Soil acidity and pH buffering	Increases soil pH by 0.17–2.2 units; reduces exchangeable aluminum (Al^{3+}) and manganese (Mn^{2+}) toxicity	Proton neutralization; base-cation (calcium (Ca^{2+}), magnesium (Mg^{2+}), and potassium (K^+)) retention; pH-mediated metal deactivation	Wang et al. 2018b; Yan et al. 2021; Liu et al. 2023b
Soil carbon dynamics and sequestration	Soil organic carbon (SOC) increased by 16–45%; total carbon (C) ↑ up to 194.6%; stable C fraction ↑ 25–40%; reduced CO_2 emissions by 20–35%	Addition of aromatic, recalcitrant C; microbial necromass stabilization; suppressed C mineralization; aggregate protection	Sun et al. 2017; Liyanage et al. 2021; Chen et al. 2024; Zeng et al. 2022
Greenhouse gas mitigation	Nitrous oxide (N_2O) reduced by 25–94%; nitric oxide (NO) reduced by 15–30%; lower global warming potential (GWP)	Enhanced *nosZ*-based denitrification; suppression of fungal denitrification; reduced nitrifier activity; pH-induced pathway shifts	Ji et al. 2020a, 2022; Zheng et al. 2019; Kim et al. 2015
Soil structure and water relations	Lower bulk density; higher porosity and water-holding capacity	Biochar porosity enhances aeration, infiltration, and moisture retention; improved aggregation	Yi et al. 2022; Zou et al. 2023; Zhang et al. 2024
Nutrient retention and mobilization	Nitrogen (N) leaching ↓ 25–40%; phosphorus (P) availability ↑ 15–84%; K availability ↑ 10–70%	Higher CEC; adsorption of ammonium (NH_4^+)/nitrate (NO_3^-); P desorption via pH increase; K supply from ash; enhanced microbial solubilization (*pqqC*, phosphatase)	Wang et al. 2018a; Li et al. 2021a; Wei et al. 2025; Zhang et al. 2025a
Micronutrient dynamics	Increased plant zinc (Zn) and Mg; reduced Mn toxicity; improved Ca uptake	pH-regulated solubility; micronutrient contribution from ash; Mg/Ca enrichment via modified biochars	Li et al. 2021a; Sarmah et al. 2023; Yan et al. 2021
Microbial diversity and function	Shannon index ↑ 15–28%; beneficial Proteobacteria, Actinobacteria increase; Acidobacteria decrease; enzyme activities ↑ 30–60%	Biochar microhabitats; alkaline shift favors copiotrophs; higher enzyme activities (urease, phosphatase, β-glucosidase); increased functional genes (*amoA*, *nirK*/*nirS*, *nosZ*)	Han et al. 2022b; Ji et al. 2020a; Jiang et al. 2021; Luo et al. 2023
Heavy-metal immobilization	Lead (Pb) ↓ 40–61%; cadmium (Cd) ↓ 35–70%; chromium (Cr) ↓ 25–48%; nickel (Ni) ↓ 20–35%; reduced metal uptake by tea leaves	Surface complexation; sorption; ion exchange; pH-induced precipitation; metal redistribution from labile to stable fractions	Borgohain et al. 2022; Liu et al. 2023b; Yan et al. 2021
Tea yield and quality	Yield ↑ 10–40%; improved amino acids, polyphenols, catechins; better root growth	Enhanced nutrient uptake; reduced Al toxicity; better root morphology and photosynthesis; plant growth-promoting rhizobacteria (PGPR) synergy	Manzoor et al. 2022; Yang et al. 2021; Li et al. 2024a
Optimal application parameters	Effective range: 5–30 t ha^{-1} (≈2.5–5% w/w); optimal responses commonly at 15–20 t ha^{-1}; recommended pyrolysis temperature: 500–600 °C	Balance between pH buffering, nutrient retention, and structural benefits; higher temperatures increase aromaticity and surface area	Han et al. 2022a, b, 2023a, b; Jiang et al. 2021; Ji et al. 2020a, 2020b; Li et al. 2018; Wang et al. 2023a; Yang et al. 2024; Zhang et al. 2025a

and function, stabilize SOC, and reduce GHG emissions and heavy metal uptake in *Camellia sinensis*. These benefits are strongly influenced by biochar feedstock, pyrolysis conditions, application rate, and interactions with organic and mineral amendments. Moderate biochar rates generally deliver the most consistent improvements, while the newly reviewed dose–response patterns highlight diminishing or adverse effects at excessively high application rates. At the same time, substantial geographical and methodological gaps persist, particularly the lack of field trials in major tropical tea-producing regions. Recent work on microbial mechanisms, nutrient cycling, and metal immobilization provides valuable insights, yet further refinement is needed before robust, globally applicable recommendations can be made. Looking forward, the transition from promising experimental findings to standardized, scalable practices will require long-term, multi-site field studies that integrate soil, microbial, and plant performance indicators with robust biochar characterization protocols. Addressing emerging risks including micronutrient imbalance, potential contaminant introduction, short-term N immobilization, and context-dependent N_2O mitigation will be essential to ensure safe and effective implementation. As the tea industry faces mounting pressures from soil degradation, climate change, and market demand for high-quality and environmentally responsible production, biochar represents a viable, climate-smart amendment with considerable potential to support sustainable management. Continued investment in interdisciplinary research, region-specific field evaluation, and improved biochar governance will be critical for unlocking its full agronomic and environmental value in global tea cultivation.

Abbreviations

AMF	Arbuscular mycorrhizal fungi
BF	Biochar-based fertilizer
CEC	Cation exchange capacity
GHG	Greenhouse gas
GWP	Global warming potential
MCP	Microbial carbon pump
NUE	Nutrient use efficiency
PAH	Polycyclic aromatic hydrocarbon
PGPR	Plant growth-promoting rhizobacteria
SOC	Soil organic carbon
SOM	Soil organic matter

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1007/s42773-026-00580-5.

Additional file 1.

Author contributions

Md Shafiqul Islam: Conceptualization, investigation, writing—original draft and visualization. Shangwen Xia: Conceptualization—review and editing.

Funding

This work was supported by the National Foreign Expert Project, China (grant number Y20240123).

Data availability

No new data were created or analyzed for the research described in the article.

Declarations

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

During the preparation of this work, the authors used DeepSeek and ChatGPT (GPT-4.5 and GPT-5.0–5.2) to enhance the clarity and quality of the English language. After using these tools and services, the authors reviewed and edited the content as needed and took full responsibility for the content of the published article.

Competing interest

The author declares no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

Author details

[1]Laboratory of Tropical Forest Ecology, Xishuangbanna Tropical Botanical Garden, Chinese Academy of Sciences, Mengla 666303, Yunnan, China. [2]Yunnan Key Laboratory of Forest Ecosystem Stability and Global Change, Xishuangbanna Tropical Botanical Garden, Chinese Academy of Sciences, Mengla 666303, Yunnan, China.

Received: 21 September 2025 Revised: 7 January 2026 Accepted: 14 January 2026
Published online: 09 March 2026

References

Akgül G, Maden TB, Diaz E, Jiménez EM (2019) Modification of tea biochar with Mg, Fe, Mn and Al salts for efficient sorption of PO_3^{-4} and Cd^{2+} from aqueous solutions. J Water Reuse Desalin 9:57–66. https://doi.org/10.2166/wrd.2018.018

Amarasinghe HAHI, Gunathilake SK, Karunarathna AK (2016) Ascertaining of optimum pyrolysis conditions in producing refuse tea biochar as a soil amendment. Procedia Food Sci 6:97–102. https://doi.org/10.1016/j.profoo.2016.02.021

Borgohain A, Sarmah M, Konwar K, Gogoi R, Gogoi B, Khare P, Kumar Paul R, Handique JG, Malakar H, Deka D, Saikia J, Karak T (2022) Tea pruning litter biochar amendment in soil reduces arsenic, cadmium, and chromium in made tea (*Camellia sinensis* L.) and tea infusion: A safe drink for tea consumers. Food Chem X 13:100255. https://doi.org/10.1016/j.fochx.2022.100255

Chen J, Wei X, Hu J, Shi Y, Zhang J, Zheng F (2024) Effect of biochar-based fertilizer on temperature sensitivity of soil organic carbon mineralization in aged tea gardens. Chin J Agrometeorol 45:245–256. https://doi.org/10.3969/j.issn.1000-6362.2024.03.003. (**in Chinese**)

Chen L, Guo L, Zhou Q, Liu M, Zhan S, Pan X, Zeng Y (2022a) Response of soil fertility and Cu and Cd availability to biochar application on paddy soils with different acidification levels. Biomass Convers Biorefinery 12:1493–1502. https://doi.org/10.1007/s13399-020-00917-5

Chen X, Wu C, Li Q, Zhou P, Chen Z, Han Y, Shi J, Zhao Z (2022b) Effect of thermophilic microbial agents on antibiotic resistance genes and microbial communities during co-composting of pig manure and tea stalks. Sustainability. https://doi.org/10.3390/su141912593

Dong X, Xu H, Ren Y, Lin D, Li K, He J (2025) Phosphoric acid and magnesium chloride composite-modified biochar improved pakchoi growth by reducing Pb and Cd accumulation and altering soil properties and microbial communities. Horticulturae 11:632. https://doi.org/10.3390/horticulturae11060632

Ghorbani M, Amirahmadi E, Bernas J, Konvalina P (2024) Testing biochar's ability to moderate extremely acidic soils in tea-growing areas. Agronomy. https://doi.org/10.3390/agronomy14030533

Gotore O, Philip T, Tatenda M (2024) The immobilization and adsorption mechanisms of agro-waste based biochar : a review on the effectiveness of pyrolytic temperatures on heavy metal removal. Environ Chem Ecotoxicol 6:92–103. https://doi.org/10.1016/j.enceco.2024.04.002

Guo S, Liu Y, Zhang W, Wang Y, Xiao B, Gao Y (2022) N-doped carbon fibers in situ prepared by hydrothermal carbonization of *Camellia sinensis* branches waste for efficient removal of heavy metal ions. Environ Sci Pollut Res 29:88951–88961. https://doi.org/10.1007/s11356-022-21923-2

Guo S, Wang Y, Wei X, Gao Y, Xiao B, Yang Y (2020) Structural analysis and heavy metal adsorption of N-doped biochar from hydrothermal carbonization of *Camellia sinensis* waste. Environ Sci Pollut Res 27:18866–18874. https://doi.org/10.1007/s11356-020-08455-3

Han X, Hy Y, Zheng NG (2023a) Nitrous oxide emissions from tea plantations: a review. Chin J Appl Ecol 34:805–814. https://doi.org/10.13287/j.1001-9332.202303.011. (**in Chinese**)

Han Z, Lin H, Xu P, Li Z, Wang J, Zou J (2022a) Impact of organic fertilizer substitution and biochar amendment on net greenhouse gas budget in a tea plantation. Agric Ecosyst Environ 326:107779. https://doi.org/10.1016/j.agee.2021.107779

Han Z, Xu P, Li Z, Guo S, Li S, Liu S, Wu S, Wang J, Zou J (2023) Divergent effects of biochar amendment and replacing mineral fertilizer with manure on soil respiration in a subtropical tea plantation. Biochar 5. https://doi.org/10.1007/s42773-023-00273-3

Han Z, Xu P, Li Z, Lin H, Zhu C, Wang J, Zou J (2022b) Microbial diversity and the abundance of keystone species drive the response of soil multifunctionality to organic substitution and biochar amendment in a tea plantation. GCB Bioenergy 14:481–495. https://doi.org/10.1111/gcbb.12926

He Z, Xia W, Zhou W, Tian Y, Liu W, Lin S (2016) Effects of wheat-straw derived biochar on acidified tea garden soil N_2O and CO_2 emission in short-term laboratory experiments. Ecol Environ Sci 25:1230–1236. https://doi.org/10.16258/j.cnki.1674-5906.2016.07.020. (**in Chinese**)

Hu Y, Wang Y, Tang Y, Yang H, Fan S, Zeng Y, Zhang Y, Wu Y, Wang G (2024) Biochar combined with organic fertilizer improved soil quality, promoted the growth of *Cunninghamia lanceolata* (Lamb.) Hook and changed the microbial community. Écoscience 31:149–164. https://doi.org/10.1080/11956860.2024.2406162

Islam MS, Chen Y, Weng L, Ma J, Khan ZH, Liao Z, Magid ASIA, Li Y (2021a) Watering techniques and zero-valent iron biochar pH effects on As and Cd concentrations in rice rhizosphere soils, tissues and yield. J Environ Sci. https://doi.org/10.1016/j.jes.2020.07.002

Islam MS, Deng H, Dong Y, Zhu J, Gao M, Song Z (2024) Improving arsenic and cadmium contaminated paddy soil health and rice quality with plant-animal-based modified biochar: a mechanistic study. J Clean Prod 448:141659. https://doi.org/10.1016/j.jclepro.2024.141659

Islam MS, Magid ASIA, Chen Y, Weng L, Arafat MY, Khan ZH, Ma J, Li Y (2021b) Arsenic and cadmium load in rice tissues cultivated in calcium enriched biochar amended paddy soil. Chemosphere 283:131102. https://doi.org/10.1016/j.chemosphere.2021.131102

Islam MS, Zhu J, Xiao L, Khan ZH, Saqib HSA, Gao M, Song Z (2023) Enhancing rice quality and productivity: multifunctional biochar for arsenic, cadmium, and bacterial control in paddy soil. Chemosphere 342:140157. https://doi.org/10.1016/j.chemosphere.2023.140157

Ji C, Han Z, Zheng F, Wu S, Wang J, Wang J, Zhang H, Zhang Y, Liu S, Li S, Zou J (2022) Biochar reduced soil nitrous oxide emissions through suppressing fungal denitrification and affecting fungal community assembly in a subtropical tea plantation. Agric Ecosyst Environ 326:107784. https://doi.org/10.1016/j.agee.2021.107784

Ji C, Li S, Geng Y, Miao Y, Ding Y, Liu S, Zou J (2020a) Differential responses of soil N_2O to biochar depend on the predominant microbial pathway. Appl Soil Ecol 145:103348. https://doi.org/10.1016/j.apsoil.2019.08.010

Ji C, Li S, Geng Y, Yuan Y, Zhi J, Yu K, Han Z, Wu S, Liu S, Zou J (2020b) Decreased N2O and NO emissions associated with stimulated denitrification following biochar amendment in subtropical tea plantations. Geoderma 365:114223. https://doi.org/10.1016/j.geoderma.2020.114223

Jiang Y, Wang X, Zhao Y, Zhang C, Jin Z, Shan S, Ping L (2021) Effects of biochar application on enzyme activities in tea garden soil. Front Bioeng Biotechnol 9:1–8. https://doi.org/10.3389/fbioe.2021.728530

Kim YJ, Park H, Kim M-H, Seo SH, Ok YS, Yoo G (2015) A study of burcucumber biochars to remediate soil Pb considering GWP (Global Warming Potential). J Korean Soc Environ Eng 37:432–440. https://doi.org/10.4491/ksee.2015.37.7.432. (**in Korean**)

Li C, Lyu Y, Zhang M, Jiang R, Feng Y, Yang Z (2017) Influence of pyrolysis conditions on properties of tea residue biochar and its passivation effect in Cd contaminated soil. Chin J Environ Eng 11:6504–6510. https://doi.org/10.12030/j.cjee.201703050. (**in Chinese**)

Li C, Yang W, Zhou B, Zhang Y, Lin Y, Xing S (2021a) Effects of biochar-based fertilizer on soil nutrients, tea output and quality in an acidified tea field. Chin J Soil Sci 52:387–397. https://doi.org/10.19336/j.cnki.trtb.2020090301. (**in Chinese**)

Li L, Guo X, Zhao T, Li T (2021b) Green waste composting with bean dregs, tea residue, and biochar: effects on organic matter degradation, humification and compost maturity. Environ Technol Innov 24:101887. https://doi.org/10.1016/j.eti.2021.101887

Li W, Xie P, Zhou H, Zhao H, Yang B, Xiong J (2024a) Preparation of Lanthanum-modified tea waste biochar and its adsorption performance on fluoride in water. Materials 17. https://doi.org/10.3390/ma17030766

Li X, Qi Y, Zhang X, Chen Z, Chen W, Zhao B, Ren D, Zhang S (2024b) Influence of modified biochar on soil fluoride and cadmium speciation and their bioavailability to tea seedling (*Camellia Sinensis* L.). Soil Sediment Contam an Int J 33:612–633. https://doi.org/10.1080/15320383.2023.2228415

Li Y, Li Z, Lin W-W, Jiang Y, Weng B, Lin W-X (2018) Effects of biochar and sheep manure on rhizospheric soil microbial community in continuous ratooning tea orchards. Chin J Appl Ecol 29:1273–1282. https://doi.org/10.13287/j.1001-9332.201804.036

Li Y, Wang H, Li Z, Ye J, Wang Y (2022) Ameliorative effect of several measures on soil physicochemical properties and microbial community structures in acidified tea gardens. J Tea Sci 42:661–671. https://doi.org/10.13305/j.cnki.jts.2022.05.009. (**in Chinese**)

Liu W, Cui S, Ma J, Wu D, Ye Z, Liu D (2023a) Effects of shellfish and organic fertilizer amendments on soil nutrients and tea yield and quality. Toxics 11. https://doi.org/10.3390/toxics11030262

Liu W, Luo Y, Zhu X, Dong D, Wang M, Ma J, Ye Z, Liu D (2025) Optimizing tea plantation productivity: magnesium-modified tea pruning litter biochar enhances soil quality and tea aroma profiles. Environ Technol Innov 40:104375. https://doi.org/10.1016/j.eti.2025.104375

Liu W, Tang Y, Ma J, Zhang W, Liao S, Cui S, Ye Z, Liu D (2023b) Effects of biochar and inorganic amendments on soil fertility, tea yield, and quality in both Pb–Cd-contaminated and acidified tea plantations. J Soils Sediments 23:3275–3284. https://doi.org/10.1007/s11368-023-03523-w

Liyanage LRMC, Sulaiman MF, Ismail R, Gunaratne GP, Dharmakeerthi RS, Rupasinghe MGN, Mayakaduwa AP, Hanafi MM (2021) Carbon mineralization dynamics of organic materials and their usage in the restoration of degraded tropical tea-growing soil. Agronomy. https://doi.org/10.3390/agronomy11061191

Lu K, Yang X, Gielen G, Bolan N, Ok YS, Niazi NK, Xu S, Yuan G, Chen X, Zhang X, Liu D, Song Z, Liu X, Wang H (2017) Effect of bamboo and rice straw biochars on the mobility and redistribution of heavy metals (Cd, Cu, Pb and Zn) in contaminated soil. J Environ Manage 186:285–292. https://doi.org/10.1016/j.jenvman.2016.05.068

Luo M, Liu T, Huang J, Xu H, Jiang T, Xie X, Yang Y (2025) Heavy metal(oid)s in soil–tea system: sources, bioaccumulation, and risks in Eastern Dabie Mountain. Land 14:1269. https://doi.org/10.3390/land14061269

Luo Y, Zhang Y, Wang Y, Sun Y, Xia X, Su Y, Liao W (2023) Combined application of biochar and pruned tea plant litter benefits nitrogen availability for tea and alters microbial community structure. Agronomy. https://doi.org/10.3390/agronomy13061465

Manzoor Ma L, Ni K, Ruan J (2024) Influence of organic and inorganic fertilizers on tea growth and quality and soil properties of tea orchards' top rhizosphere soil. Plants 13:1–22. https://doi.org/10.3390/plants13020207

Manzoor Ma L, Ni K, Ruan J (2022) Effect of integrated use of rapeseed cake, biochar and chemical fertilizers on root growth, nutrients use efficiency and productivity of tea. Agronomy 12. https://doi.org/10.3390/agronomy12081823

Mayakaduwa SS, Vithanage M, Karunarathna A, Mohan D, Ok YS (2016) Interface interactions between insecticide carbofuran and tea waste biochars produced at different pyrolysis temperatures. Chem Spec Bioavailab 28:110–118. https://doi.org/10.1080/09542299.2016.1198928

Min X, Ge T, Li H, Shi Y, Fang T, Sheng B, Li H, Dong X (2022) Combining impregnation and co-pyrolysis to reduce the environmental risk of

biochar derived from sewage sludge. Chemosphere 290:133371. https://doi.org/10.1016/j.chemosphere.2021.133371
Mohan D, Abhishek K, Patel M, Jr, CUP (2024) Harnessing biochar in contaminated soil for heavy metal immobilization, soil health enhancement, and carbon sequestration. Ind Eng Chem Res 63. https://doi.org/10.1021/acs.iecr.4c00082
Peng Q, Wang P, Yang C, Liu J, Si W, Zhang S (2024) Remediation effect of walnut shell biochar on Cu and Pb co-contaminated soils in different utilization types. J Environ Manage 362:121322. https://doi.org/10.1016/j.jenvman.2024.121322
Qian J, Cai QS, Huang XH, Zhou XY, Wu JZ, Xiao KC, Liu YC (2023) Effect of tea residue biochar on nitrogen adsorption-desorption characteristics and improvement of soil acidity of an acidic tea garden soil. Res Agric Mod 44:922–932. https://doi.org/10.13872/j.1000-0275.2023.0077. (**in Chinese**)
Rebello R, Burgess PJ, Girkin NT (2022) Identifying sustainable nitrogen management practices for tea plantations. Nitrogen 3:43–57. https://doi.org/10.3390/nitrogen3010003
Sahoo K, Upadhyay A, Runge T, Bergman R, Puettmann M, Bilek E (2021) Life-cycle assessment and techno-economic analysis of biochar produced from forest residues using portable systems. Int J Life Cycle Assess 26:189–213. https://doi.org/10.1007/s11367-020-01830-9
Saleem I, Lahori AH, Mierzwa-Hersztek M, Afzal A, Muhammad MT, Ahmed MS, Vambol V, Vambol S (2024) The application of MgO-modified biochars for the immobilization of Ni, Cu, Pb, and Cr in stone crushing and mining-polluted soil. Agronomy. https://doi.org/10.3390/agronomy14071423
Sarmah M, Borgohain A, Gogoi BB, Yeasin M, Paul RK, Malakar H, Handique JG, Saikia J, Deka D, Khare P, Karak T (2023) Insights into the effects of tea pruning litter biochar on major micronutrients (Cu, Mn, and Zn) pathway from soil to tea plant: an environmental armour. J Hazard Mater 442:129970. https://doi.org/10.1016/j.jhazmat.2022.129970
Shirvanimoghaddam K, Czech B, Tyszczuk-Rotko K, Kończak M, Fakhrhoseini SM, Yadav R, Naebe M (2021) Sustainable synthesis of rose flower-like magnetic biochar from tea waste for environmental applications. J Adv Res 34:13–27. https://doi.org/10.1016/j.jare.2021.08.001
Shu Q, Gao S, Liu X, Yao Z, Wu H, Qi L, Zhang X (2025) Soil enzyme activities and microbial carbon pump promote carbon storage by influencing bacterial communities under nitrogen-rich conditions in tea plantation. Agriculture. https://doi.org/10.3390/agriculture15030238
Sipayung HN, Wu KT, Liu DY, Chen CT (2022) Growth enhancement of *Camellia sinensis* with biochar. Processes. https://doi.org/10.3390/pr10020199
Sun Y, Shaaban M, He Z, Zhang S, Lin S (2017) Effects of biochar on tea garden soil amelioration and tea quality. Soil Fertil Sci China 6:9–14. https://doi.org/10.11838/sfsc.20170602. (**in Chinese**)
Wang F, Chen Y, You Z, Wu Z, Jiang F, Zhang W (2015) Effect of biochar (*Camellia sinensis*) addition on nitrogen leaching in strong acid tea garden soils. J Soil Water Conserv 29. https://doi.org/10.13870/j.cnki.stbcxb.2015.01.023. (**in Chinese**)
Wang F, Wu Z, Chen Y, Jiang F, Zhu L, Wenjin Z, Weng B, You Z (2018a) Effects of the combined application of biochar and nitrogen on growth and nitrogen use efficiency of tea plants. J Tea Sci 38:331–341. https://doi.org/10.13305/j.cnki.jts.2018.04.001. (**in Chinese**)
Wang H, Hu T, Wang M, Liang Y, Shen C, Xu H, Zhou Y, Liu Z (2023a) Biochar addition to tea garden soils: effects on tea fluoride uptake and accumulation. Biochar 5. https://doi.org/10.1007/s42773-023-00220-2
Wang Z, Liu S, Ruan Y, Wang Q, Zhang Z (2023b) Comparison of biochar- and lime-adjusted pH changes in N_2O emissions and associated microbial communities in a tropical tea plantation soil. Agronomy 13. https://doi.org/10.3390/agronomy13041144
Wang J, Zhang B, Tian Y, Zhang H, Cheng Y, Zhang J (2018b) A soil management strategy for ameliorating soil acidification and reducing nitrification in tea plantations. Eur J Soil Biol 88:36–40. https://doi.org/10.1016/j.ejsobi.2018.06.001
Wang S, Junling C, Xiaojie Z, Yanchun LI, Hua C, Yixiang W (2025) Impacts of substituting chemical fertilizer with organic fertilizer in conjunction with biochar on soil aggregate stability and accumulation of organic carbon in tea plantations. Chin J Trop Crop 46:937–947. https://doi.org/10.3969/j.issn.1000-2561.2025.04.016. (**in Chinese**)
Wei W, Li K, Li C, Wang S, Li L, Xie J, Li T, Zhou Z, Zhang S, Pu Y, Jia Y, Liu X, Xu X, Wang G (2025) Enhancing soil phosphorus and potassium availability in tea plantation: the role of biochar, PGPR, and phosphorus- and potassium-bearing minerals. Agronomy 15. https://doi.org/10.3390/agronomy15061287
Wu P, Xie M, Clough TJ, Yuan D, Wu S, He X, Hu C, Zhou S, Qin S (2023) Biochar-derived persistent free radicals and reactive oxygen species reduce the potential of biochar to mitigate soil N_2O emissions by inhibiting *nosZ*. Soil Biol Biochem 178:108970. https://doi.org/10.1016/j.soilbio.2023.108970
Yan P, Shen C, Zou Z, Fu J, Li X, Zhang L, Zhang L, Han W, Fan L (2021) Biochar stimulates tea growth by improving nutrients in acidic soil. Scientia Hortic 283:110078. https://doi.org/10.1016/j.scienta.2021.110078
Yang W, Li C, Wang S, Zhou B, Mao Y, Rensing C, Xing S (2021) Influence of biochar and biochar-based fertilizer on yield, quality of tea and microbial community in an acid tea orchard soil. Appl Soil Ecol 166. https://doi.org/10.1016/j.apsoil.2021.104005
Yang Z, Ren Z, Zhu X, Yang W, Ye Z, Tian L, Ma J (2025) Biochar-based fertilizer increases soil nutrients and enhances tea quality: a metabolomics-based analysis. Front Plant Sci 16:1–14. https://doi.org/10.3389/fpls.2025.1552759
Yang Z, Yao B, Li R, Yang W, Dong D, Ye Z, Wang Y, Ma J (2024) Systematic review assessing the effects of amendments on acidic soils pH in tea plantations. PeerJ 12:1–22. https://doi.org/10.7717/peerj.17653
Yi X, Ji L, Hu Z, Yang X, Li H, Jiang Y, He T, Yang Y, Ni K, Ruan J (2022) Organic amendments improved soil quality and reduced ecological risks of heavy metals in a long-term tea plantation field trial on an Alfisol. Sci Total Environ 838:156017. https://doi.org/10.1016/j.scitotenv.2022.156017
Yin R, Li L, Liu H, Yao J, Ma C, Pu L, Lei Z (2024) Biochar, organic fertilizer, and bio-organic fertilizer improve soil fertility and tea quality. Agronomy. https://doi.org/10.3390/agronomy14102339
Yin R, Li X, Ning Y, Hu Q, Mao Y, Zhang X, Zhang X (2025) Machine learning unveils the role of biochar application in enhancing tea yield by mitigating soil acidification in tea plantations. Sci Total Environ 965:178597. https://doi.org/10.1016/j.scitotenv.2025.178597
Zeng X, Xiao X, Xia J, Xian S (2022) Effect of biochar from tea residue on the mineralization of soil organic carbon in Mingshan tea garden. J Sichuan Agric Univ 40 (**in Chinese**). https://doi.org/10.16036/j.issn.1000-2650.202104038
Zhang B, Liu C, Li Q, Ye J, Lin Y, Wang Y, Burton DL (2025a) Evaluating the effect of biochar rate and combination with fertilizer on the dynamics of soil nitrogen supply in tea plantation. Sci Rep 15:1–12. https://doi.org/10.1038/s41598-025-87942-4
Zhang S, Huang F, Guo S, Luo Y, Zhang L, Zhang L, Li Z, Ge S, Wang H, Fu J, Li X, Yan P (2025b) Mitigation of soil organic carbon mineralization in tea plantations through replacement of pruning litter additions with pruning litter derived biochar and organic fertilizer. Ind Crops Prod 225:120518. https://doi.org/10.1016/j.indcrop.2025.120518
Zhang SH, Shen Y, Lin LF, Tang SL, Liu CX, Fang XH, Guo ZP, Wang YY, Zhu YC (2024) Effects of bamboo biochar on soil physicochemical properties and microbial diversity in tea gardens. PeerJ 12:1–18. https://doi.org/10.7717/peerj.18642
Zhang SH, Wang Y, Hu JJ, Chen WJ, Wu JL, Seah RWX, Zhu YC, Guo ZP, Chen J (2023) Bamboo charcoal affects soil properties and bacterial community in tea plantations. Open Life Sci 18:1–11. https://doi.org/10.1515/biol-2022-0681
Zhao JJ, Huang XH, Hua LL, Zhou SS, Jiang W, Tang YC, Qian J (2022) Effects of tea residue biochar on phosphorus adsorption-desorption in soil. Polish J Environ Stud 31:2461–2471. https://doi.org/10.15244/pjoes/143357
Zheng N, Yu Y, Shi W, Yao H (2019) Biochar suppresses N_2O emissions and alters microbial communities in an acidic tea soil. Environ Sci Pollut Res 26:35978–35987. https://doi.org/10.1007/s11356-019-06704-8
Zongwei Z, Haonan L, Junqi L, Zihan W, Xiaojun Y, Wenjie L, Xinyuan W, Shuiting D (2025) LCA and TEA analyses of bio-jet fuel prepared from *Arundo donax*. Sustain Energy Technol Assessments 75:104233. https://doi.org/10.1016/j.seta.2025.104233
Zou Z, Fan L, Li X, Dong C, Zhang L, Zhang L, Fu J, Han W, Yan P (2021) Response of plant root growth to biochar amendment: a meta-analysis. Agronomy 11:1–14. https://doi.org/10.3390/agronomy11122442
Zou Z, Mi W, Li X, Hu Q, Zhang L, Zhang L, Fu J, Li Z, Han W, Yan P (2023) Biochar application method influences root growth of tea (*Camellia sinensis* L.) by altering soil biochemical properties. Sci Hortic. https://doi.org/10.1016/j.scienta.2023.111960