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Biochar and Humic Substances Roles for Nitrogen Transformation in Agriculture

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ABSTRACT

Sustainable soil fertility management is crucial for global food security and addressing environmental challenges from modern agriculture. Soil health, alongside water availability, is essential for crop productivity, and soil degradation threatens food security by lowering yields and intensifying climate change. Nitrogen (N) cycling is central to soil fertility, supporting plant growth through nutrient replenishment and microbial activity. However, N is often lost through leaching, volatilization, and denitrification, reducing nitrogen use efficiency (NUE) and contributing to water pollution and greenhouse gas (GHG) emissions. Optimizing nitrogen retention in soils is vital for improving productivity and minimizing environmental harm. Biochar (BC) and humic substances (HSs) have emerged as effective strategies for improving N management. BC enhances soil fertility by increasing soil pH, cation exchange capacity, and water retention, while reducing nutrient leaching and promoting carbon sequestration. HSs, including humic acids (HA), fulvic acids (FA) and humin (HU), improve nutrient cycling by stimulating microbial activity and enhancing nutrient transport. Together, BC and HSs provide synergistic benefits for soil health, particularly in challenging environments like saline or nutrient-depleted soils. This review highlights the roles of BC and HSs in enhancing soil fertility, promoting N mineralization, and improving crop productivity. It emphasizes their potential for sustainable agricultural practices, climate change mitigation, and long-term soil health.

LIST OF ABBREVIATIONS

APX	*: Ascorbate Peroxidase*	*GPX*	*: Glutathione Peroxidase*	*NH_4^+*	*: Ammonium*
As	*: Arsenic*	*HA*	*: Humic Acid*	*NO_2^-*	*: Nitrite*
BC	*: Biochar*	*Hg*	*: Mercury*	*NO_3^-*	*: Nitrate*
BGU	*: β-glucosidase*	*HU*	*: Humin*	*NUE*	*: Nitrogen Use Efficiency*
CAT	*: Catalase*	*HSs*	*: Humic Substances*	*P*	*: Phosphorus*
C	*: Carbon*	*K*	*: Potassium*	*POX*	*: Peroxidase*
CEC	*: Cation Exchange Capacity*	*Mg^{2+}*	*: Magnesium*	*PTAL*	*: Phenylalanine/Tyrosine Ammonia-Lyase*
Cu^{2+}	*: Copper*	*Mn^{2+}*	*: Manganese*	*ROS*	*: Reactive Oxygen Species*
DOM	*: Dissolved Organic Matter*	*MeHg*	*: Methylmercury*	*SOC*	*: Soil Organic Carbon*
FA	*: Fulvic Acid*	*N*	*: Nitrogen*	*SOM*	*: Soil Organic Matter*
Fe^{2+}	*: Iron*	*N_2O*	*: Nitrous Oxide*	*THMs*	*: Trihalomethanes*
GHG	*: Greenhouse Gas*	*NH_3*	*: Ammonia*		

1. INTRODUCTION

The sustainable management of soil fertility is vital for ensuring global food security and addressing the environmental challenges posed by modern intensive agriculture (Nadarajah, 2022; Mi *et al*., 2023). Soil health, together with water availability, is among the most crucial resources for humanity, as our existence relies on the soil's productivity. Therefore, soil degradation presents a serious threat to food security by reducing crop yields, forcing farmers to increase input usage, potentially leading to the abandonment of farmland, and exacerbating climate change (Gomiero, 2016; Bagnall *et al*., 2021).

Nutrient cycling, particularly nitrogen cycling, is essential for maintaining soil fertility and supporting plant growth. It ensures a continuous supply of nutrients, replenishes soil fertility, and supports microbial activity crucial for decomposing organic matter (Nair *et al*., 2021; Ding *et al*., 2024; Gabasawa *et al*., 2024). Nitrogen (N), a key nutrient in plant growth, plays an essential role in critical metabolic processes such as protein synthesis and chlorophyll production, which influences crop yields and quality (Zayed *et al*., 2023). Despite its importance, N is often lost from agricultural soils through processes like leaching, volatilization, and denitrification (Adhikary *et al*., 2020; Zayed *et al*., 2023). These losses reduce nitrogen use efficiency (NUE) and contribute to environmental issues, including water contamination and increased greenhouse gas (GHG) emissions (Ntinyari *et al*., 2022). Optimizing N transformation and retention in soils is therefore crucial to enhancing crop productivity and minimizing environmental harm (Ren *et al*., 2022; Zhu *et al*., 2024).

In recent years, the application of biochar and humic substances has emerged as a promising strategy for improving nitrogen management in soils (Yadav *et al*., 2023; Ghadirnezhad Shiade *et al*., 2024). Biochar (BC), a carbon (C)-rich material produced by pyrolyzing organic biomass, has shown significant potential to enhance various soil properties, such as nutrient retention, water holding capacity, and microbial activity (Yadav *et al*., 2023). Likewise, humic substances (HSs)—complex organic compounds formed from the decomposition of plant and animal matter—are instrumental in nutrient cycling, improving soil structure, and facilitating microbial activity, which in turn supports the availability and transformation of essential nutrients like nitrogen (Tiwari *et al*., 2023). The interplay between BC, HSs, and N dynamics in soil systems is both intricate and multifaceted, influencing not only the immediate availability of nitrogen for plants but also long-term soil fertility (Sun *et al*., 2022).

This review seeks to investigate the unique properties of BC and HSs, their impact on soil organic matter (SOM), and their roles in N mineralization and transformation processes. Additionally, it will explore the synergistic effects of BC and HSs on soil fertility and discuss their implications for sustainable agricultural practices. By synthesizing recent research and practical insights, this paper aims to highlight the potential of BC and HSs as effective tools for improving N management, enhancing crop yields, and promoting environmental sustainability in agriculture.

2. BIOCHAR EFFECTS ON SOIL ORGANIC MATTER (SOM)

Biochar (BC) is a robust material produced from biomass via thermochemical conversion processes under high-temperature conditions with limited or no oxygen, resulting in a C-rich product with steady physical and chemical traits (Agarwal *et al*., 2017; Ravindiran *et al*., 2024). BC, a C-dense material, is derived from agricultural and forestry waste, including crop residues such as wheat straw, corn stubble, and rice hulls, as well as forestry waste materials like pistachio shells, sugarcane fiber, pine wood, walnut shells, palm residues, eucalyptus green waste, algal residues, and animal and poultry waste (Wang *et al*., 2020; Masud *et al*., 2023). When the pyrolysis process occurs at temperatures between 450°C and 700°C, a relatively uniform microporous structure appears on the BC surface. The different feedstocks used for producing biochar result in distinct characteristics (Tomczyk *et al*., 2020; Jin *et al*., 2024).

The structure of BC is marked by numerous pores and a high level of aromatization. Its physical and chemical characteristics are largely determined by the type of feedstock, the pyrolysis method, and the temperature applied during the carbonization process. When it's produced at lower carbonization temperatures, it generally contains higher levels of plant-available nutrients like potassium (K) and phosphorus (P), in contrast to biochar generated at higher temperatures. However, BC produced at pyrolysis temperatures of 550°C or above usually shows an increased cation exchange capacity (CEC, though this can vary depending on the measurement method), a larger specific surface area, and a higher pH. The variety of functional groups present on the surface of BC is significantly affected by the pyrolysis temperature. Consequently, the pyrolysis temperature is a key factor in determining the BC's characteristics (Ippolito *et al*., 2020; Sakhiya *et al*., 2020; Tomczyk *et al*., 2020; Janu *et al*., 2021; Leng *et al*., 2021; Haider *et al*., 2024). As the pyrolysis temperature rises, the water retention capacity of BC typically decreases. This is due to the increased aromatization, the decline in C- and N-containing functional groups, and greater hydrophobicity, all of which lead to reduced water conductivity (Zhang *et al*., 2022; He *et al*., 2024). Research indicates that activated C possesses pores, with 95% of them having a diameter smaller than 2 nm. Additionally, the water-holding capacity of BC is also affected by the feedstock materials used in its production (Jin *et al*., 2024).

Due to these unique properties, incorporating BC into soil can affect various aspects of the soil micro-environment. Research highlights that BC application boosts soil organic carbon (SOC) levels by about 27%, with more noticeable improvements in both coarse and fine-textured soils. Additionally, BC enhances microbial diversity, particularly in medium and coarse-textured soils, by providing a suitable environment for beneficial soil microbes, which are essential for breaking down organic matter, cycling nutrients, and controlling soil-borne pathogens. Furthermore, BC improves nutrient retention by minimizing nutrient loss through leaching and gaseous emissions, leading to better N retention and increased P availability in the soil. This, in turn, contributes to higher crop productivity, especially in fine and coarse-textured soils (Hossain *et al*., 2020; Singh *et al*., 2022a; Singh *et al*., 2022b).

3. HUMIC SUBSTANCES (HSs) EFFECTS ON SOIL ORGANIC MATTER (SOM)

Humic substances (HSs) are organic molecules formed through the decomposition of plant and animal materials, typically found in soil, peat, and water. Structurally, HSs are intricate and made up of polydisperse mixtures of molecules connected by subtle interactions like hydrogen bonding and hydrophobic attractions, making them difficult to detach in their genuine form (Rupiasih &Vidyasagar, 2005; Tiwari *et al*., 2023). The bulk of soil humic substances (HSs) consists of humic acid (HA), with fulvic acid (FA) and humin (HU) present in lesser amounts. Humic acid (HA) has a molecular weight ranging from 10^4 to 10^5 Dalton (Da), assembling into large molecular complexes. Conversely, fulvic acid (FA) has a significantly lower molecular weight, generally ranging from 600 to 1,500 Da (Diallo *et al*., 2003; Rupiasih & Vidyasagar, 2005). The comparative characteristics of HA, FA, and HU are presented in Table 1.

Table 1. Comparative characteristics of humic substances (HSs) components: humic acid (HA), fulvic acid (FA), and humin (HA)

Characteristics	Humic substances (HSs) components		
	Humic Acid (HA)	**Fulvic Acid (FA)**	**Humin (HU)**
Solubility	Insoluble at pH < 1-2 (acidic conditions)	Soluble at all pH values	Insoluble in all pH values
Appearance	Dark brown to grey-black	Light yellow to yellow brown	Black
Degree of polymerization	Intermediate	Lowest	Highest
Acidity	Highest acidity	Less acidic than FA	Least acidic
Elemental composition	Higher C and lower O content compared to FA	Higher O and lower C content compared to HA	Highest C and lowest O content
Functional groups	Contains free and bound phenolic OH groups, quinone structures, COOH groups	Contains more acidic functional groups, particularly -COOH	Contains various functional groups, less characterized
Molecular weight	Higher than FA	Lower than HA	Highest
Reactivity	Reacts with metals, influences soil quality and productivity	High capability for complexation with metals and various compounds	Reacts with soil or sediment, forms coatings for clay minerals
Applications in agriculture	Soil amendments, improve soil properties, nutrient retention, PGP, stress resistance	Soil amendments, nutrient chelation, transport of nutrient, antioxidant properties, photosynthesis enhancement	Long-term soil carbon storage, improve soil physical properties (aggregation and stability)
Research challenges	Well-studied due to its role in agriculture	Increasingly studied for its application in agriculture	Less understood due to its complex structure and low reactivity

Abbreviation: C = carbon; FA = fulvic acid; HA = humic acid; HU = humin; PGP = plant growth promotor; O = oxygen.

Humic acid (HA) is a key component of HSs, distinguished by its solubility in alkaline environments and insolubility in acidic conditions and water. Known as an important high-molecular-weight element of organic fertilizers, HA contains functional groups such as phenolic hydroxyl, carbonyl, amino, and carboxyl groups, enabling it to efficiently interact with heavy metals via mechanisms such as complexation, redox reactions, and adsorption. HA also plays a vital role in enhancing plant resistance to reactive oxygen species (ROS) during drought by activating H^+-ATPase and promoting phenylalanine/tyrosine ammonia-lyase (PTAL) activity. Its antioxidant properties allow it to scavenge ROS, thereby increasing plant resilience to stress. Moreover, HA enhances the net photosynthetic rate and reduces transpiration in plants under drought conditions, while its ability to bind with heavy metals helps alter soil structure and restricts the movement of these metals (Heidari Dehno & Mohtadi, 2018; Francini *et al*., 2019; Gan *et al*., 2019; Kansara *et al*., 2021; Tiwari *et al*., 2023; Vasic *et al*., 2023).

Fulvic acid (FA) is identified as a component of HSs that stays soluble even after acidification. It has gained increasing importance in areas like ecological restoration, medicine, and contemporary agriculture. One of its main features is its abundant phenolic and carboxyl groups, which contribute to FA's strong overall acidity. In agriculture, FA acts as a biostimulant, enhancing plant growth, productivity, and nutrient uptake. FA, primarily consists of C, H, O, and N, is water-soluble across all pH levels, and its dissolution in water creates a series of negative charges that increase with rising pH. This behavior is primarily due to carboxylic type groups at lower pH levels, particularly below pH 7. FA mainly originates from polysaccharides and low molecular weight fatty acids (Kononova, 2013; Rajneesh Kumar *et al*., 2021; Tiwari *et al*., 2023).

Humin (HU) is a constituent of HSs that remains insoluble in alkaline aqueous solutions. HU cannot be extracted from soil using either acidic or neutral solutions. As a crucial part of SOM, HU is known for its low reactivity and the challenges it poses for research. HU possesses a higher molecular weight and degree of polymerization than HA and FA, which indicates its superior stability and long-lasting effects in soil. Its furan-rich structure, revealed by two-dimensional solid-state nuclear magnetic resonance spectroscopy, is linked by aliphatic chains, which enhances its durability. Increased HU content plays a key role in improving soil health, boosting HSs storage, and facilitating carbon sequestration. Despite its significance, there is still limited knowledge about the molecular structure, characteristics, and formation mechanisms of HU (Kononova, 2013; van Zandvoort *et al*., 2015; Qi *et al*., 2020; Tiwari *et al*., 2023).

HSs are crucial for enhancing soil health, playing multifaceted roles such as improving nutrient availability, regulating moisture levels, and acting as buffers against pH changes. These compounds also foster the growth of beneficial soil microbes, which are vital for nutrient cycling and enhancing soil structure. HSs also promotes plant resilience against abiotic stresses, leading to improved growth and productivity. Their role in carbon sequestration significantly contributes to the reduction of atmospheric CO_2 levels, further highlighting their importance in sustainable agriculture and environmental conservation (Tiwari *et al*., 2023).

4. BC AND HSs ROLES ON NITROGEN (N) MINERALIZATION

N mineralization involves transforming organic N compounds (including proteins, amino acids, and other organic substances) into inorganic forms, such as ammonium (NH_4^+) or nitrate (NO_3^-), which plants can easily take up. The process of N mineralization involves several key steps. First, during ammonification, soil microorganisms, primarily bacteria and fungi, decompose organic N compounds, such as proteins, into simpler forms, resulting in the release of NH_4^+. Following this, the process of nitrification occurs in two stages: initially, nitrifying bacteria oxidize NH_4^+ to produce nitrite (NO_2^-); subsequently, NO_2^- is further oxidized to form NO_3^-. Finally, plants absorb these inorganic N forms, namely NH_4^+ and NO_3^-, through their roots, utilizing them for growth and metabolic functions (Kandeler, 1996; Elrys *et al*., 2021; Yagüe & Lobo, 2021).

The porous structure of BC provides a larger surface area, which allows for effective adsorption of NH_4^+ ions. Functional groups, such as carboxyl and ester, present on the BC surface further enhance this adsorption capacity (Trazzi *et al*., 2024). The pores in BC serve as habitats for soil microorganisms, which are essential for converting organic N into inorganic forms. BC provides these microorganisms with vital C and N, supporting their growth and activity. Appropriate macropores can protect less competitive microorganisms from predators, thus improving their chances of survival (Dai *et al*., 2021; Jin *et al*., 2024). When organic N is stabilized by aged BC, its transformation into inorganic forms is more gradual, leading to a slow release that boosts soil fertility and supports plant nutrition over time (Wang *et al*., 2020; Masud *et al*., 2023). Additionally, BC raises soil pH naturally due to its alkaline content, including ash and carbonates (such as Ca_2^+, K^+, and Mg_2^+), which helps to neutralize soil acidity (Hailegnaw *et al*., 2019; Šimanský *et al*., 2024). These properties enable BC to retain nutrients effectively, reducing their leaching and enhancing their availability for plant uptake (Wang *et al*., 2020).

However, it's important to exercise caution when soil pH exceeds 7. In highly alkaline conditions, the N present as ammonium NH_4^+ in the soil can be converted into NH_3 through the process of volatilization. As pH increases, more NH_4^+ transitions into NH_3, which can escape into the atmosphere, reducing the N available for crops (Pan *et al*., 2021). This lowers nitrogen use efficiency (NUE), negatively affecting crop yields and environmental sustainability (Hung *et al*., 2021). To minimize NH_3 volatilization, it is crucial to carefully manage BC application rates and monitor soil pH, particularly in soils that are already neutral or slightly alkaline (Egyir *et al*., 2022; Qi *et al*., 2022).

HSs contain functional groups like carboxyl and phenolic groups that bind to metal ions such as Fe^{2+}, Mn^{2+}, Cu^{2+}. When HSs chelate metal ions, they create soluble complexes that can transport essential nutrients, including N, within the soil solution. This process also prevents metal ions from forming insoluble precipitates with P and other anions, which indirectly enhances N availability (He *et al*., 2016). The availability of these nutrients stimulates microbial activity. Active microbes decompose organic matter more efficiently (Gadd, 2013; Mahala *et al*., 2020). HSs effect on microbial activity could indirectly influence the production of proteases and NH_4^+ produced enzymes which are needed for N mineralization. Protease enzymes decompose organic nitrogen from proteins into amino acids. Then, enzymes that produce NH_4^+, like urease, transform organic N into NH_4^+ (Gadd, 2013; Razzaq *et al*., 2019; Mahala *et al*., 2020; Piotrowska-Długosz, 2020; Solanki *et al*., 2021; Chen *et al*., 2024a; Chen *et al*., 2024b). Unlike BC, which can increase soil pH due to its alkaline nature, HSs do not directly influence pH levels. Instead, they mainly enhance nutrient availability and contribute to overall soil health. When combined with BC, HSs can experience improved stability and quality by optimizing the balance between HA and FA levels (Rahim *et al*., 2024).

5. CURRENT RESEARCH AND PRACTICAL APPLICATIONS OF BC AND HSs

The use of BC and HSs has gained recognition as an effective approach to improving soil quality, boosting plant growth, and reducing environmental impacts in agriculture. Numerous studies have highlighted their benefits in both short- and long-term applications, particularly regarding soil enzyme activity, nutrient availability, carbon storage, and water quality. By enhancing soil properties, microbial activity, and nutrient dynamics, biochar presents a valuable solution to various agricultural challenges, such as saline soils, heavy metal pollution, and GHG emissions. Additionally, their roles in agricultural production, co-composting, digestate enrichment, and land reclamation have been extensively explored in recent research.

5.1. The role of BC and HSs in soil improvement and sustainable agriculture

The integration of BC and HSs with manure has demonstrated significant improvements in soil properties and plant growth, particularly in the early stages of application. Studies over 12 and 24 weeks showed that BC and HSs-enriched manure increased nutrient content, enzyme activity, and plant biomass, with P availability enhancing soil microbiota and plant development. However, over time, these benefits diminished, especially as BC-induced C accumulation reduced β-glucosidase (BGU) enzyme activity, indicating the need for ongoing management (Holatko *et al.*, 2022b). Long-term studies on poultry litter (PL) and poultry litter biochar (PLB) further highlighted the benefits of BC, showing that while PL promoted rapid organic matter mineralization, PLB's slower rates contributed to improved stability of SOM, enhancing humic acid C stability and reducing CO_2 emissions, thus offering a sustainable solution for soil quality improvement and C sequestration (Jarosz *et al*., 2022). Additionally, BC's impact on water quality through the leaching of dissolved organic matter (DOM) underscores the importance of selecting appropriate biochar types, as corn biochar exhibited the highest risk for harmful disinfection by-products like trihalomethanes (THMs) (Lee *et al*., 2018).

Bioaugmentation, which involves adding microbial agents and BC to co-composting processes, plays a vital role in enhancing humification and overall agricultural production. This technique boosts humification through the Maillard and polyphenol pathways, reduces C and N losses, and promotes a slow release of nutrients. In co-composting, the breakdown of lignocellulosic materials increases total N content, with microbial agents proving more effective than BC in promoting humification. However, BC creates an ideal environment for microorganisms by improving aeration and providing a stable structure for microbial activity. For example, co-composting corn straw with biogas slurry not only efficiently recovers nutrients but also generates bio-heat, as demonstrated by the treatment of 1 kg of corn straw with 2.5 L of biogas slurry. BC also aids in N retention by fostering the formation of C–N bonds within HA, which is especially beneficial during composting processes involving materials like chicken manure and rice straw. This bioaugmentation process helps retain nitrogen and supports the formation of HSs, contributing to long-term soil fertility (Cao *et al*., 2023).

In addition, combining BC and Humac—a HA-rich material from low-grade coals like lignite and leonardite—has shown potential for enhancing nutrient dynamics and C capture when used with digestate. In pot experiments with maize, Humac-enriched digestate improved short-term nutrient conversion and increased plant biomass. However, while BC initially improved nutrient retention, long-term results showed nutrient immobilization, which hindered mineralization and nutrient availability to plants (Holatko *et al*., 2022a).

BC has also proven effective in reducing GHG emissions, particularly nitrous oxide (N_2O), which is a potent contributor to global warming. A 90-day experiment conducted on loamy sand Spodosol demonstrated that BC application reduced cumulative N_2O emissions by 1.4 times compared to untreated soil and fertilizer treatments. This reduction in emissions is attributed to the ability of BC to improve soil aeration and alter redox conditions, leading to increased enzymatic activities, such as catalase (CAT) and peroxidase (POX), which help mitigate N_2O fluxes (Rizhiya *et al*., 2017). Similarly, incorporating BC into food waste digestate composting has proven effective in reducing N loss and speeding up composting. A 10% BC addition reduced NH_4^+ emissions by 58%, N loss by 50%, and helped compost reach maturity in just 15 days (Manu *et al*., 2021).

5.2. BC and HSs for environmental remediation

Saline soils pose significant challenges for agriculture, primarily due to salt accumulation, which hampers plant growth. BC, particularly poultry litter biochar (PBC) and hydrochar (HBC), has been found to mitigate some of these effects. Lower application rates of PBC and HBC reduce ammonia (NH_3) volatilization and enhance SOM and total N content. However, higher doses of HBC increase NH_3 volatilization and the leaching of dissolved organic matter (DOM), complicating soil management. While BC application at moderate levels improves rice yields, excessive BC–especially PBC–can increase soil salinity, reducing crop productivity. These findings emphasize the importance of precise BC dosage to balance its benefits and risks in saline soils, demonstrating BC's potential for saline-alkali soil remediation and improving crop growth when applied correctly (Ma *et al*., 2024).

In the context of arsenic (As) contamination, which poses serious threats to rice production and food safety, BC combined with HA shows promise in reducing the harmful effects of As on rice plants. The joint application of BC and HA boosts the activity of antioxidant enzymes such as ascorbate peroxidase (APX), glutathione peroxidase (GPX), and catalase (CAT), helping plants mitigate oxidative stress caused by As toxicity. This combination also improves the plants' water regulation, membrane stability, and electrolyte balance, enhancing their overall resilience. Additionally, BC and HA improve soil nutrient availability, reduce the bioavailability of heavy metals, and promote photosynthesis and growth under As stress, making them effective soil amendments in contaminated fields (Hasanuzzaman *et al*., 2024).

Another environmental challenge in rice cultivation is methylmercury (MeHg) contamination. Sulfur (S)-enriched BC, particularly from oilseed rape straw, has been shown to reduce MeHg levels in rice. This type of biochar increases chloride and sulfate concentrations, encouraging microbial activity that can methylate mercury (Hg). However, it also increases HA-like substances in the soil, reducing MeHg levels in rice grains by 47% to 75%. These results suggest that S-enriched BC can effectively lower the uptake of Hg in rice crops, offering a sustainable solution to manage toxic metal contamination and improve food safety (Hu *et al*., 2021).

In degraded and poor-quality soils, such as those found in mine reclamation sites, the use of BC combined with HA and super absorbent polymers can significantly improve soil properties. Pot experiments conducted in China demonstrated that this composite material improved soil bulk density, porosity, and nutrient availability. The optimal blend, consisting of 3 $g \cdot kg^{-1}$ of super absorbent polymer, 3 $g \cdot kg^{-1}$ of HA, and 10 $g \cdot kg^{-1}$ of BC, was found to be most effective in enhancing soil structure and fertility. Additionally, the application of these materials had a profound impact on soil microbial communities. Beneficial bacterial groups such as Acidobacteria, Bacteroidetes, Chloroflexi, and Proteobacteria were positively correlated with improvements in soil health and plant growth, while other groups like Actinobacteria exhibited negative correlations. These shifts in microbial diversity were closely tied to enhancements in soil physicochemical properties and the promotion of plant root biomass. This underscores the critical role of microbial communities in maintaining soil health and productivity, particularly in reclamation projects and nutrient-poor environments (Li *et al*., 2020).

6. CONCLUSION

Biochar (BC) and humic substances (HSs) play critical roles in transforming nitrogen (N) in agricultural soils, particularly in improving soil fertility and enhancing crop production. Both materials have distinct yet complementary characteristics that contribute to soil health, nutrient retention, and the overall N mineralization process, essential for plant growth and productivity. BC, with its unique porous structure and high carbon (C) content, provides a favourable habitat for soil microorganisms and enhances the retention of nutrients, particularly nitrogen. By increasing soil pH, cation exchange capacity (CEC), and water retention, BC supports the slow release of N, reduces nutrient leaching, and enhances overall soil fertility. This is particularly important in agriculture fields where N management is critical for sustaining crop yields. BC's ability to stabilize soil organic matter (SOM) and contribute to long-term carbon sequestration also offers significant environmental benefits, including reducing greenhouse gas (GHG) emissions and mitigating climate change. Humic substances (HSs), including humic acid (HA), fulvic acid (FA), and humin (HU), act as organic catalysts in nutrient cycling. They enhance the availability of N by binding metal ions and improving the transport of essential nutrients in the soil. HSs stimulate microbial activity, promoting the decomposition of organic nitrogen compounds and accelerating the nitrogen mineralization process. By improving soil structure, enhancing nutrient uptake, and increasing plant resilience to stress, HSs serve as critical components in sustainable agricultural practices. Their ability to chelate metals and improve soil's physical and chemical properties makes them valuable for long-term soil health. The integration of BC and HSs offers synergistic benefits. Together, they improve nutrient retention, enhance microbial activity, and promote nitrogen mineralization, all of which contribute to improved crop productivity and soil quality. These combined effects are particularly valuable in challenging agricultural environments, such as saline soils, heavy metal-contaminated soils, and nutrient-depleted soils, where BC and HSs have been shown to remediate soil conditions, enhance nutrient availability, and boost plant growth.

Recent research and practical applications have demonstrated the effectiveness of BC and HSs in improving soil quality, promoting plant growth, and contributing to environmental sustainability. Their roles in reducing GHG emissions, managing soil contamination, and enhancing carbon sequestration are of particular importance in the context of global agricultural sustainability and climate change mitigation. However, their benefits are highly dependent on proper management, including optimal application rates, feedstock selection, and understanding their long-term effects on soil properties. Future research should aim to refine application techniques, evaluate long-term impacts, and optimize the integration of biochar into agricultural systems for maximum benefit, while also exploring BC and HSs performance in composting at lower C/N ratios to reduce the need for bulking agents and improve overall processing efficiency.

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