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Review Article

Biochar and Vermicompost Synergies; Intgrated for Soil Health and Sustainable Management-A Review

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Abstract

Soil Health and sustainable management are fundamental to sustainable, playing a critical role in maintain crop productivity, protecting the environment, and ensuring the long-term viability of agriculture system. Soil health is the continued capacity of soil to function as a vital living ecosystem that sustains plant, animals and humans by supporting biological productivity, preserving air and water quality and promoting overall well-being. Integrated, ecofriendly soil fertility management combines organic and inorganic impute such as fertilizers, composts and crop residues with conservation practice tailored to local condition. This improves soil structure, enhance mutant availability, boosts microbial activity restores degraded soil and increase crop yields in cost effective and environmental responsible way. Biochar is a carbon rich material produced by heating biomass like wood or manure in limited oxygen at temperature below 700 ℃. it improve soil fertility, water retention, pH, aeration organic matter, cation exchange capacity while reducing nutrient leaching and greenhouse gas emission like N_2O and CH_4. Its porous structure and surface functional groups help in contaminates control and carbon sequestration. Vermicomposting is a biological processes where earthworms convert organic into nutrient rich vermicomposting. It operate at moderate temperature and produce casting rich in microbial life, plant growth hormones and pest repelling compounds. Verimcopost improve aeration, porosity, water retention, pH, conductivity and organic matter. Combined use of biochar and vermicomposting enhancing soil fertility, reduce salinity, immobilizes heavy metal and suppresses plant diseases and pests.

Keywords

Soil Fertility, Organic Matter, Vermicomposting, Water Retention, Microbial Activity

1. Introduction

Soil Health and sustainable management are fundamental sustainable agriculture, playing a critical role maintaining crop productivity, protecting the environment and ensuring the long-term viability of agriculture system [1]. Soil health is the continued capacity of soil to function as a vital living ecosystem that sustains plants, animals, and humans. It is the soil's ability to perform within an ecosystem by supporting biological productivity, preserving air and water quality, and promoting the well-being of plants, animals, and people [2-4].

Organic amendments such as compost and manure restore soil fertility by providing nutrients, enhancing structure, and boosting microbial activity. Soil organic matter (SOM) plays a vital role in maintaining soil health by improving its physical, chemical, and biological characteristics. Additions like

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crop residues, Biochar, compost, and other organic byproducts increase SOM levels and contribute to the recovery of degraded soils [5, 6].

Integrated, eco-friendly soil fertility management is essential for maintaining health soil and supporting sustainable agriculture. This approach combines organic and inorganic input such as tailored to local conditions. By improving soil structure, enhancing nutrient availability, and boosting microbial activity, it helps restore degraded soils and increases crop yields in a cost-effective and environmentally responsible way. These practices also contribute to food security, combat soil degradation, and reduce the risks of deforestation and desertification [1, 7, 8].

Sustainable soil management ensures that soils continue to provide essential ecosystem services supporting, provisioning, regulating, and cultural without degrading their fundamental functions or biodiversity. It focuses on improving soil health while balancing crop productivity with environmental protection, including water quality, availability, and greenhouse gas control. Integrated soil fertility management is a key component of this approach, helping to sustain crop production and preserve vital ecosystem functions, thereby supporting the long-term health of both farming systems and the planet [1, 7, 9].

Biochar (BC) is a carbon-rich material produced by heating biomass like wood or manure in limited oxygen at temperatures below 700 ℃. It improves soil fertility and helps reduce atmospheric CO_2. BC enhances soil properties such as water retention, pH, aeration, organic matter, and cation exchange capacity. It also reduces nutrient leaching and greenhouse gas emissions like N_2O and CH_4. Its porous structure and surface functional groups aid in contaminant control. BC contributes to carbon sequestration and soil health. These benefits make it valuable for sustainable agriculture and environmental protection [10-12].

Vermicomposting is a biological process where earthworms convert organic waste into nutrient-rich vermicompost. Unlike traditional composting, it operates at moderate temperatures (10–32 ℃) and works faster due to the activity of earthworms and microbes. The resulting worm castings are rich in microbial life, plant growth hormones, and pest-repelling compounds. Vermicompost improves soil physically (aeration, porosity, water retention) and chemically (pH, conductivity, organic matter), enhancing plant growth. Its benefits go beyond nutrients, likely due to humic acids and hormones like auxins and cytokines. However, excessive use may slow plant growth, so proper application is important. Overall, vermicompost is a powerful organic fertilizer and soil enhancer, offering a sustainable alternative to chemical fertilizers [13-15].

The aim of this seminar is explore the synergistic potential of biochar and vermicompost integrate approaches to improve soil health and promoting sustainable soil management. By focusing on the role of organic amendments, we will examine strategies to enhance soil fertility, boost long-term agricultural productivity, and support environmental sustainability through effective, eco-friendly practices.

2. Methodology of Review

This review paper provide a comprehensive analysis of Biochar and Vermicompost synergies; integrated approaches for soil health and sustainable managements. The methodology involved a systematic review of the literature, including peer-reviewed journal articles, reports, theses, and books published in English. Relevant studies were selected based on their relevance to the topic, research methodology, and outcomes. A comprehensive search was conducted using keywords such as "Soil health," "Biochar," "Vermicompost," "Soil fertility," and "Sustainable agriculture" in databases like Google Scholar, Science Direct, and Web of Science. Initial screening resulted in the retrieval of 42 articles, and after reviewing titles, abstracts, and full texts, 29 articles were selected for further analysis. Of these, 75% were sourced from Google Scholar and 25% from Web of Science and Science Direct. The studies were categorized into two main themes: the synergistic effect of biochar and vermicompost on soil health, and their influence on sustainable management. The articles were then compared and contrasted based on their findings and methodologies to provide a balanced overview of the existing literature. Additionally, the study explored future research directions and potential concerns related to the effect of biochar and vermicompost synergies effect on soil health and sustainable management.

3. Discussion

Vermicompost significantly improve soil health by enhancing microbial activity soil structure, nutrient availability, and water retention, leading to increased crop yields, better seed germination, and natural disease resistance [16]. As a slow-release, nutrient-rich fertilizer made from organic waste such as agricultural residues, manure, and urban waste, vermicompost serves as a sustainable alternative to chemical fertilizers [16, 17]. Alongside biochar which improves soil fertility, crop quality, and sustainability vermicomposting supports eco-friendly farming by recycling nutrients and promoting long-term agricultural productivity [18].

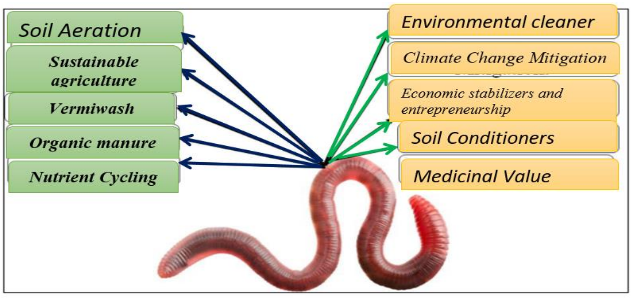

Figure 1. Showing the role of earthworms in different aspect of sustainable environment and life on biosphere [19].

Biochar is beneficial for soil health and crop growth, especial in acidic soil due its high pH from alkaline minerals and carbonate. However in neutral or alkaline can disrupts nutrient balance and microbial activity. For example biosocial improve nitrogen dynamics respiration more effectively than pin- derived biochar showing that biochar effect vary. Therefore, biochar type and application must be matched carefully to soil conditions to avoid negative impacts [20].

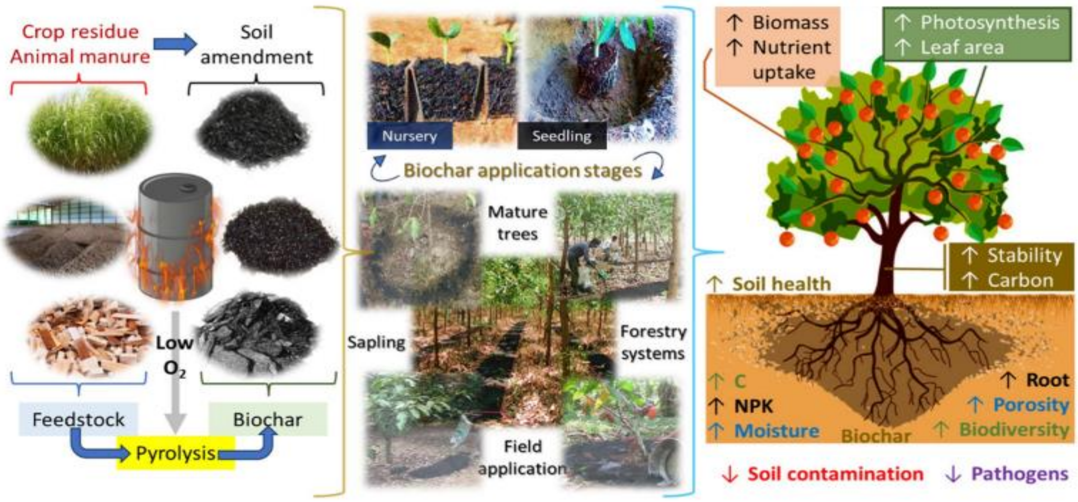

Figure 2. Pathway from feedstock to biochar use in tree crops, improving soil, ecology, carbon storage, and crop growth [20].

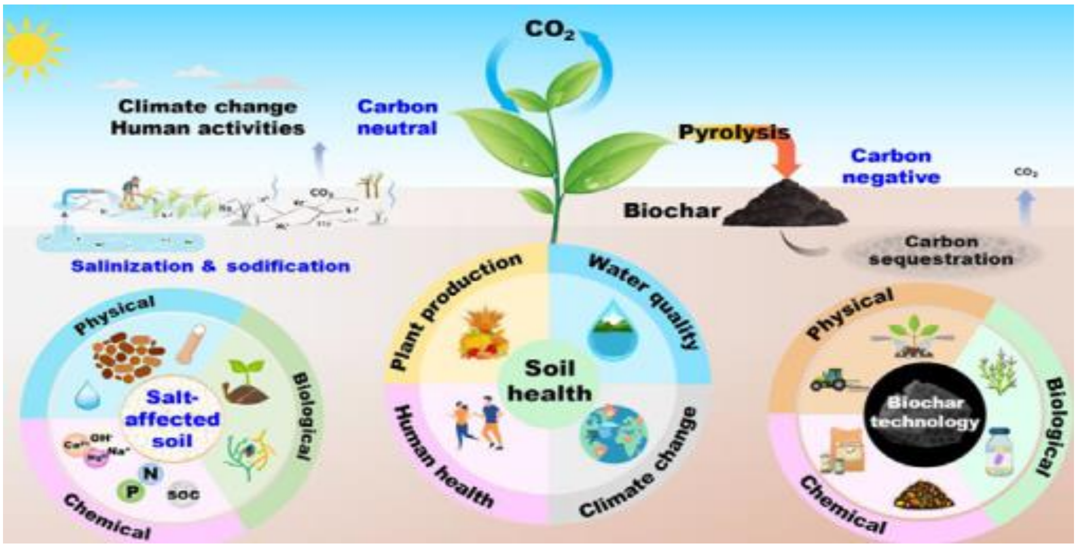

Figure 3. Schematic diagram showing the physical, chemical and biological Pathway of biochar [21].

3.1. Effects of Biochar and Vermicompost on the Soil Physicochemical Properties of Soil

3.1.1. Effect of Biochar on the Physicochemical Properties

Biochar significant improve the physicochemical property od soil, which are essential for nutrient retention, plant growth and microbial activity [22].

It enhance key soil characteristics including water infiltration, water holding capacity (WHC) aggregate stability, aeration, porosity bulk density pH, cation exchange capacity (CEC) and nutrient cycling. Soil porosity, critical for aeration and water retention movements is increase with biochar by reducing bulk density and improve aggregation, with reported increase Up to 6% particular in coarse texture soil low temperature biochar offer more labile carbon promotion activity and protecting native SOC from decomposition [21, 22].

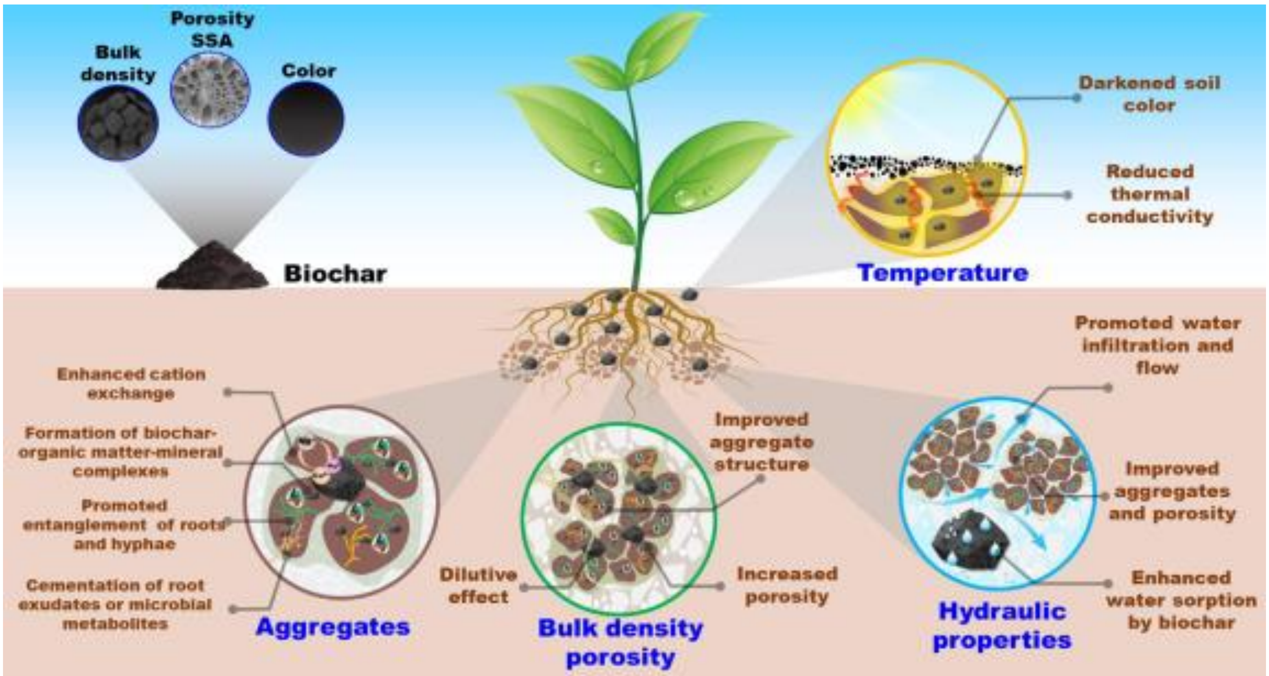

Figure 4. Schematic diagram showing the potential mechanisms underlying the positive effects of biochar amendments on the physical properties of salt-affected soils [21].

Soil improvement with biochar is attributed to enhanced aggregate formation through cation exchange, biochar-organic-mineral complexes, root and hyphae entanglement, and cementation by exudates or metabolites. Bulk density decreases and porosity increases due to the dilutive effect of biochar and better aggregate structure. Darkened soil color and reduced thermal conductivity raise topsoil temperature and buffer temperature fluctuations. Improved hydraulic properties result from greater aggregate stability, biochar's water sorption, and enhanced infiltration and flow [21, 22].

3.1.2. Effects of Vermicompost on the Physicochemical Properties

The effect of vermicompost on the physical properties of soil during the initial and final stages of samba rice cultivation in pots showed notable improvements. In the initial stage, vermicompost and vermiwash-treated post recorded a lower pH (7.0 ±0.03) and electrical conductivity (0.02 ±0.01 dS/m) Compare to control (pH 7.5 ±2.02, EC 2.12 ±1.1 dS/m), indication reduced soil salinity and improve soil reaction. Water holding capacity, porosity and moisture content were also higher in treated pots, with initial value of 49 ±1.0%, 44 ±1.0%, and 46 ±1.0%, respectively. Compare to 41 ±0.02%, 34 ±2.10%, and 36 ±1.02% in to control.

These enhancement suggest that vermicompost improve soil physical condition contribute to better moisture retention, aeration and overall soil health [23].

Table 1. Effect of Vermicompost and Vermiwash (Individual and Combined) on Physical Property Changes During Initial and Final Stages of Samba Rice Cultivation Studies [23].

Treatments	PH		Electrical Conductivity dsm-1		Water holding capacity (%)		Porosity (%)		Moisture Content (%)	
	Initial	Final	Initial	Final	Initial	Final	Initial	Final	Initial	Final
Control	7.5±2.02	7.4±2.01	2.12±1.1	2.0 ± 1.0	41±0.02	44±1.02	34±2.10	39±2.0	36±1.02	41±1.1
Vermicompost	7.4±0.01	7.1±0.01	1.02±1.0	1.01±1.0	43±0.01	47±1.0	36±1.0	41±1.0	39±1.1	44±1.0
Vermiwash	7.3±2.0	7.2±1.02	2.1±1.1	2.0±1.1	42±1.0	46±1.1	35±1.1	40±1.1	38±1.0	43±1.1
Vermicompost and vermiwash	7.0±0.03	7.0±0.03	1.01±0.01	0.02±0.01	45±0.03	49±1.0	39±0.03	44±1.0	41±1.0	46±1.0

Table 2. *Effect of Vermicompost and Vermiwash (Individual and Combined) on Chemical Property Changes During Initial and Final Stages of Samba Rice Cultivation Studies [23].*

Treatments	Nitrogen (ppm)		Phosphorous (ppm)		Potassium (ppm)		Calcium (ppm)		Magnesium (ppm)	
	Initial	Final	Initial	Final	Initial	Final	Initial	Final	Initial	Final
Control	55±2.1	61±2.0	64±2.0	69±2.0	180±2.0	184±2.1	1.0±1.0	1.5±1.0	1.0±1.0	1.5±1.0
Vermicompost	59±1.1	64±1.0	68±1.1	73±1.0	184±1.0	189±1.0	2.0±1.1	2.5±1.0	2.0±1.1	3±1.0
Vermiwash	58±1.0	63±1.1	67±1.1	72±1.1	183±1.1	188±2.0	1.5±1.1	2.0±1.0	1.2±1.1	2±1.0
Vermicompost and vermiwash	63±1.1	69±0.2	72±1.0	77±1.0	188±1.0	195±1.0	3.2±1.0	5.0±1.0	3.1±1.1	4±0.1

The effect of vermicompost on the chemical properties of soil during the initial and final stages of samba rice cultivation in pots showed significant improvements. Soils treated with a mixture of vermicompost and vermiwash recorded the highest nitrogen (69 ±0.2 ppm), phosphorus (77 ±1.0 ppm), potassium (195 ±1.0 ppm), and calcium (5.0 ±1.0 ppm) contents. In contrast, the control pots showed lower values: nitrogen (55 ±2.1 ppm), phosphorus (64 ±2.0 ppm), potassium (180 ±2.0 ppm), and calcium (1.0 ±1.0 ppm). These increases are attributed to the rich nutrient content of vermicompost and vermiwash, which enhance nutrient availability and support mineralization processes, resulting in improved soil fertility and potential crop performance [23].

Table 3. *Showing the Chronological Growth Performance of Samba Rice Cultivation with Various Vermi treatments in Two Months Interval [23].*

Treatments	Number of leaves		Leaf length (cm)		Height of the plant (cm)		Root length (cm)	
	Initial	Final	Initial	Final	Initial	Final	Initial	Final
Control	7.1+2.1	13+2.0	2.0+1.1	5+1.2	10+2.1	14+2.0	3.0+2.1	7.0+2.0
Vermicompost	9.2±1.0	16±1.0	4.0±2.0	7±1.0	14±1.0	19±1.0	6.0±1.2	12.0±1.0
Vermiwash	8.5±2.1	15±1.1	3.0±1.1	6±1.2	13±1.1	18±1.1	5.0±2.1	11.0±2.0
Vermicompost and vermiwash	12.1±1.0	19±0.1	6.0±1.0	9±0.01	17±0.1	23±0.01	7.1±1.0	15±0.01

The pot study on samba rice showed that the application of vermicompost and vermiwash significantly improved plant growth parameters compared to the control. After two months, the highest values for leaf length (19 ±0.1 cm), number of leaves (9 ±0.01), root length (15 ±0.01 cm), and plant height (23 ±0.01 cm) were recorded in treated pots. In contrast, the control pots showed much lower values: leaf length (7.1 ±2.1 cm), number of leaves (2.0 ±1.1), root length (3.0 ±2.1 cm), and plant height (10 ±2.1 cm). The improved growth in treated plants is likely due to the presence of plant growth-promoting substances and enhanced microbial activity in vermicompost [23].

Vermicompost significantly enhances soil health by improving both its physical and chemical properties, making it a valuable tool in sustainable agriculture. It reduces bulk density, increases porosity, and improves soil structure, which leads to enhanced aeration, water retention, and drainage conditions favorable for root growth and nutrient uptake [17]. The mucus secretions from earthworms and microbial activity contribute to better soil aggregation and structure stability.

Vermicompost also strengthens the water-holding capacity of the soil due to its high organic matter content, ensuring consistent moisture availability during dry periods [13]. These benefits support improved crop yield, quality, and plant health while promoting soil biodiversity and microbial activity.

Chemically, vermicompost is rich in essential nutrients like nitrogen (N), phosphorus (P), and potassium (K), and when combined with vermiwash, it significantly boosts soil fertility and nutrient availability [23]. Its slow-release properties ensure a gradual nutrient supply, enhancing mineralization and reducing nitrate accumulation compared to inorganic fertilizers an advantage for food safety and environmental health. Vermicompost also improves cation exchange capacity (CEC), aiding in long-term nutrient retention [16]. Additionally, foliar applications of vermicompost can regulate plant hormones, boost symbiotic nitrogen fixation, and improve plant growth without excessive use of chemical fertilizers, making vermicompost a key component of eco-friendly and sustainable farming systems.

3.1.3. Effect of Biochar on Nutrient Availability and Leaching

Biochar, especially when combined with vermicompost, contain significant levels of nitrogen (N), phosphorus (P), calcium (Ca), and magnesium (Mg), which contribute to enhanced plant growth characteristics. The addition of biochar improves soil physical properties by decreasing bulk density and increasing nutrient availability, allowing plant roots easier access to nutrients in the rhizosphere. Active functional groups in biochar raise the soil's cation exchange capacity, boosting nutrient absorption by plants and enhancing plant development [18, 21, 22].

Table 4. *Chemical properties of sheep- manure vermicompost and soil [24].*

Medium	pH	EC ($mScm^{-1}$)	C (%)	N (%)	P (%)	K (%)	Fe (ppm)	Mn (ppm)	Zn (ppm)	Cu (ppm)
Vermicompost	7.7	7	15	1.3	1.3	1	580	250	170	31
Soil	7.94	1.38	1.07	0.09	0.001	0.032	12	10	3	1.5

Table 5. *Effect of vermicompost on soil macroelements [24].*

Treatment with vermicompost ($t\ ha^{-1}$)	Total N (%)	P (ppm)	K (ppm)	Ca (ppm)
0	0.0700 ^{c}	5.590 ^{c}	379.00 ^{c}	144.33 ^{b}
5	0.0933 ^{bc}	10.430 ^{b}	523.00 ^{b}	168.00 ^{b}
10	0.1133 ^{ab}	13.767 ^{a}	555.67 ^{b}	227.33 ^{a}
15	0.1300 ^{a}	18.733 ^{a}	599.67 ^{a}	252.67 ^{a}

Application of vermicompost significantly improves soil chemical properties by increasing the availability of essential nutrients such as nitrogen, phosphorus, potassium, calcium, zinc, and manganese. Higher application rates (up to 15 t/ha) result in greater nutrient concentrations compared to untreated soils. Vermicompost enhances nutrient mineralization, microbial activity, and organic matter content, which contribute to better nutrient availability and soil fertility. It also leads to increased electrical conductivity and a decrease in soil pH, likely due to microbial processes and organic acid production. Overall, vermicompost enhances soil quality, making it more conducive to plant growth [24].

Table 6. *Effect of vermicompost on soil chemical and physical properties [24].*

Treatment with vermicompost ($t\ ha^{-1}$)	Zn (ppm)	Cu (ppm)	Mn (ppm)	Bulk density ($g\ cm^{-3}$)	Porosity (%)
0	2.2200 ^{b}	1.6000 ^{a}	2.4700 ^{c}	1.6933 ^{a}	35.33 ^{c}
5	2.9667 ^{ab}	1.9033 ^{a}	4.1500 ^{b}	1.6300 ^{b}	37.66 ^{b}
10	3.8400 ^{a}	1.9833 ^{a}	4.9367 ^{ab}	1.6133 ^{b}	38.66 ^{b}

Treatment with vermicompost (t ha^{-1})	Zn (ppm)	Cu (ppm)	Mn (ppm)	Bulk density (g cm^{-3})	Porosity (%)
15	4.2533 [a]	1.1400 [a]	5.7067 [a]	1.5633 [c]	40.33 [a]

Table 7. Effect of vermicompost on soil chemical properties [24].

Treatment with vermicompost (t ha^{-1})	pH	EC (mScm^{-1})	Organic carbon (%)
0	8.0000 [a]	1.2970 [c]	0.624[c]
5	7.6066 [b]	2.1183 [bc]	1.001[b]
10	7.4833 [bc]	2.8967 [ab]	1.254[ab]
15	7.3333 [c]	3.6700 [a]	1.323 [a]

Earthworms play a vital role in organic matter decomposition, consuming waste equal to their body weight daily and producing nutrient-rich castings known as vermicompost. worm castings contain nearly double the macro- and micronutrient content of traditional compost, including higher concentrations of N, P, K, Ca, and Mg, along with essential micronutrients like iron (Fe), zinc (Zn), manganese (Mn), copper (Cu), and boron (B). This nutrient richness, combined with microbial diversity, enhances soil fertility, promotes nutrient cycling, and supports disease suppression, fostering sustainable and resilient agricultural systems [16, 22].

Vermi-wash is a nutrient-rich liquid derived from water passing through vermicompost, containing earthworm excretions, mucus, soil micronutrients, enzymes, plant growth hormones, and vitamins. It is typically collected after 40–50 days as a clear, pale yellow or brownish fluid and can be used as a foliar spray or soil drench. This bio-solution promotes plant growth, improves resistance to diseases, and acts as a natural biopesticide [16]. As water filters through these burrows, it carries nutrients directly to plant roots. In the context of modern agriculture, where the excessive use of chemical inputs and water scarcity are growing concerns, vermi-wash offers an eco-friendly and sustainable alternative to support healthier crops and resilient farming systems [16, 24].

Vermicompost and biochar both contribute significantly to soil health and crop productivity. Vermicompost enhances nutrient availability, nutrient cycling, and soil structure through its high content of nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), and magnesium (Mg), most of which are in plant-available forms such as nitrate (NO_3^-). It also improves soil porosity and reduces bulk density by supporting microbial populations, increasing base exchange capacity, and oxidation potential, all of which promote plant growth and nitrogen uptake [17]. Meanwhile, biochar, rich in stable carbon and essential nutrients, enhances soil nutrient retention, carbon stability, and water-holding capacity. Its porous structure and high cation exchange capacity reduce nutrient leaching, especially in sandy soils, lowering nutrient losses (e.g., P, NH_4^+, NO_3^-) by 16–50% depending on feedstock and application rate [22, 24]. These combined properties of vermicompost and biochar improve nutrient use efficiency, reduce reliance on synthetic fertilizers, and support sustainable soil management.

3.2. Synergistic Effects on Environmental Sustainability

3.2.1. Effect on Soil Microbial Activity

Soil microorganisms play a crucial role in organic matter decomposition, nutrient cycling, soil structure maintenance, pest suppression, and plant growth promotion. Biochar positively influences microbial activity and community structure due to its porous nature, large surface area, presence of minerals and organic compounds, and its effect on soil pH. It releases essential nutrients such as potassium (K^+), magnesium (Mg^{2+}), sodium (Na^+), nitrogen (N), and phosphorus (P), which support microbial growth. Microorganisms can colonize the pores of biochar for protection, while its soluble compounds further promote microbial abundance and diversity [22].

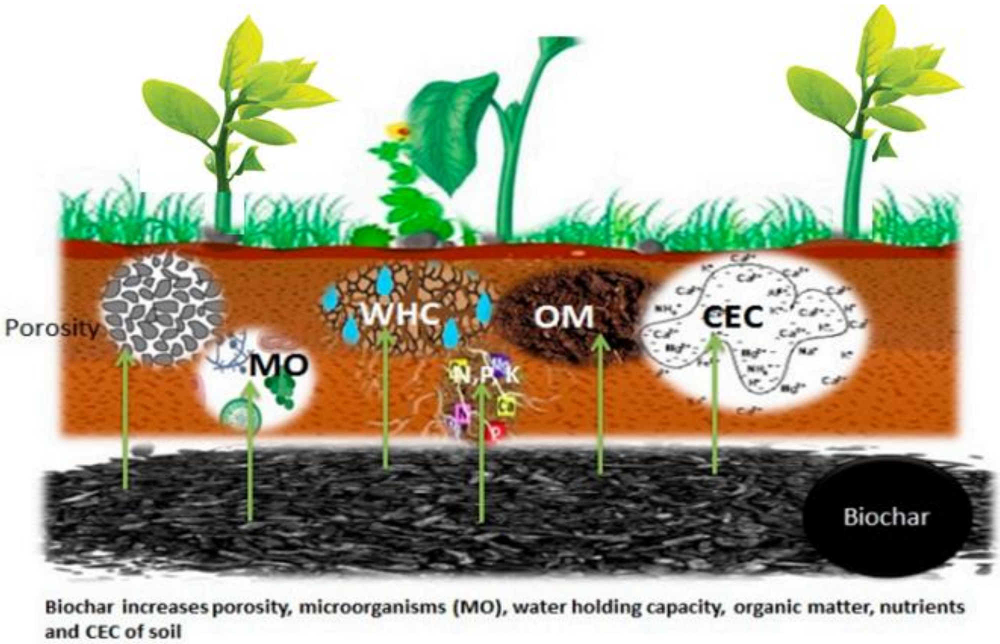

Figure 5. *Beneficial effects of biochar on soil, organic matter, water holding capacity, cation exchange capacity [22].*

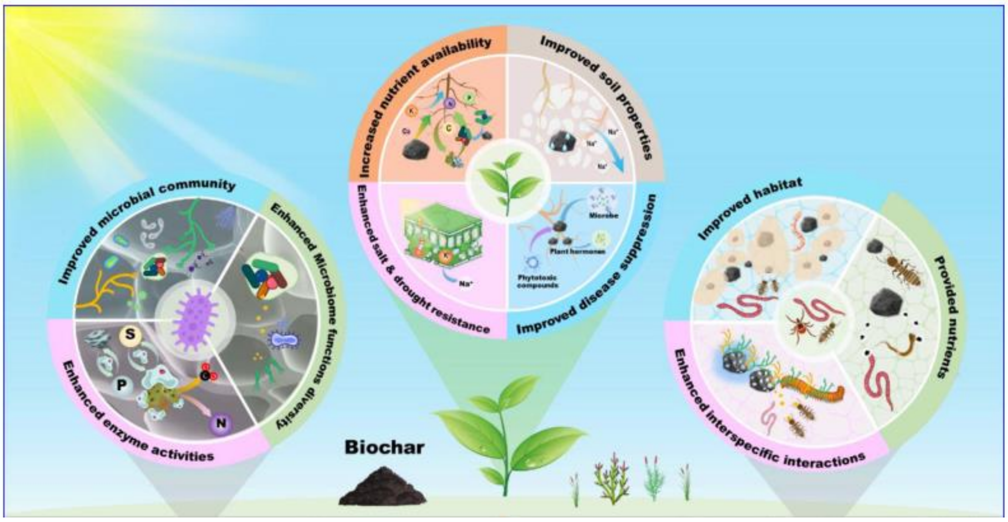

Figure 6. *Schematic diagram showing the potential mechanisms underlying the positive effects of biochar amendments on the biological properties of salt-affected soils [21].*

Biochar positively influences soil microorganisms by improving microbial communities, functional diversity, and enzyme activities through habitat provision, enhanced nutrient availability, and better soil conditions. Fauna growth benefits from improved habitats, nutrient supply, and stronger interspecies interactions. Plant growth is promoted by increased nutrient availability, improved soil properties, enhanced resistance to salt and drought, and greater disease suppression.

3.2.2. Effect on Salt-Affected Soils

Biochar and vermicompost can reduce soil salinity and conductivity through adsorption and ion exchange, which is one of the reasons for the decline in EC. Soil salinity, which affects approximately 1 billion hectares globally, poses a significant challenge to crop growth, particularly in arid and semiarid regions. Salt-affected soils categorized as saline, sodic, or saline–sodic contain high levels of soluble salts and sodium ions that impair plant nutrient uptake. Organic amendments like biochar have gained attention for their ability to improve these soils by enhancing cation exchange capacity (CEC), soil structure, and porosity [22]. Biochar increases concentrations of essential nutrients such as potassium (K^+), calcium (Ca^{2+}), magnesium (Mg^{2+}), zinc (Zn^{2+}), and manganese (Mn^{2+}), and mitigates sodium's harmful effects by boosting potassium uptake raising exchangeable K^+ by up to

44% in saline soils. Its porous structure enhances nitrogen use efficiency by adsorbing ammonium (NH_4^+) and reducing nitrogen gas losses; however, its pH influences ammonia (NH_3) volatilization, with low-pH biochars reducing and high-pH biochar increasing NH_3 loss. Additionally, in alkaline salt-affected soils, biochar improves phosphorus (P) availability by releasing P and stimulating phosphorus-solubilizing bacteria, addressing nutrient limitations caused by high pH [22].

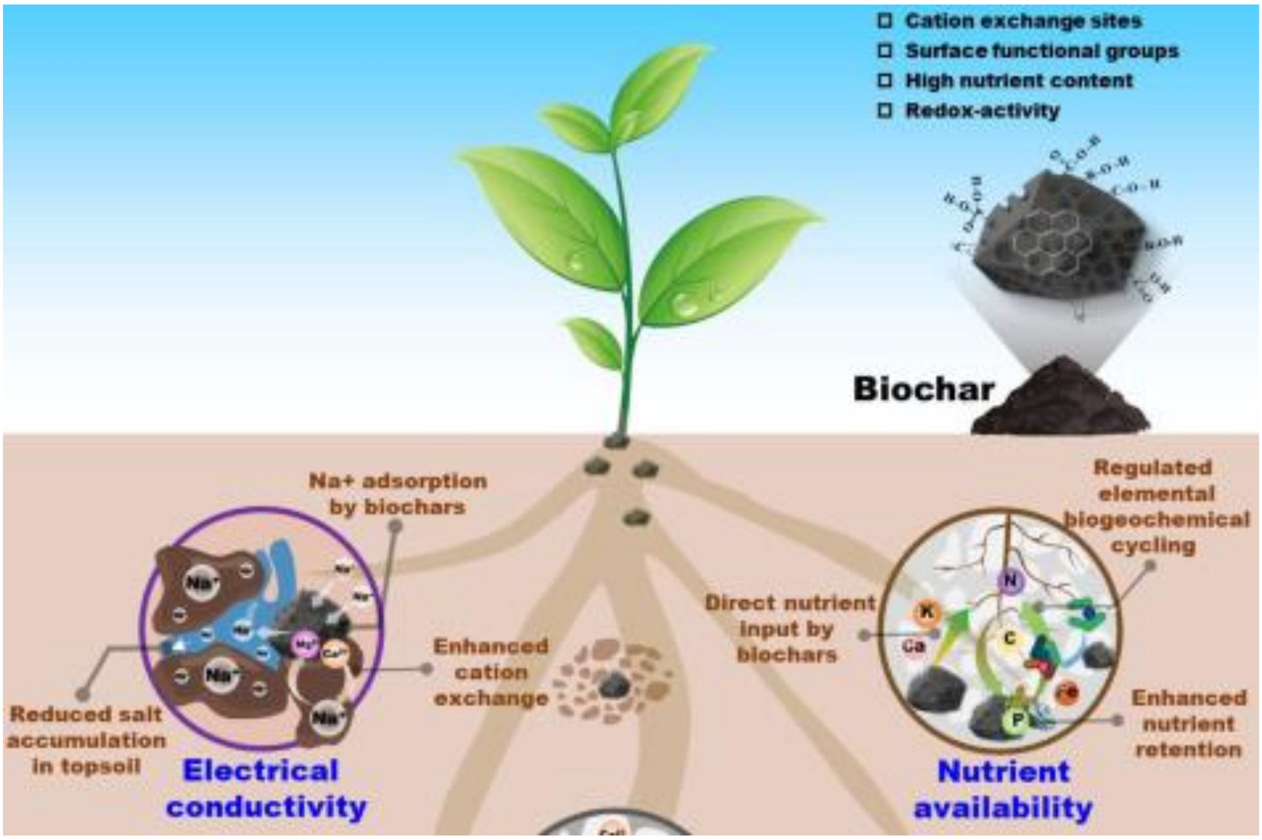

Figure 7. *Schematic diagram showing the potential mechanisms underlying the positive effects of biochar amendments on chemical properties of salt-affected soils [21].*

Biochar enhances soil health by reducing electrical conductivity through Na^+ adsorption and improved cation exchange, while lowering pH via H^+ release and H^+-Na^+ exchange. It boosts cation exchange capacity by adding exchange sites and stabilizing soil colloids. Redox potential is balanced through electron shuttling and stable radical formation. Biochar also improves nutrient availability and increases soil organic carbon by adding stable carbon, enhancing nutrient cycling, and promoting microbial carbon retention. [21, 22].

3.2.3. Vermibiochar for Heavy Metal Detox in Soils

Vermibiochar, a hybrid product of biochar and vermicompost, offers a sustainable and eco-friendly solution for mitigating heavy metal contamination in agricultural soils. Produced through the combined action of earthworms and biochar, vermibiochar possesses a high surface area, abundant functional groups, and excellent cation exchange capacity, which enhance its ability to adsorb and immobilize toxic metals such as lead, cadmium, mercury, arsenic, and chromium. By reducing the bioavailability of these metals, vermibiochar lowers their uptake by plants, thus improving soil health, crop productivity, and food safety. Additionally, its use during vermicomposting of sewage sludge further decreases heavy metal mobility and organic matter degradation, making it an effective tool for remediating polluted soils and supporting long-term sustainable agriculture [22, 25].

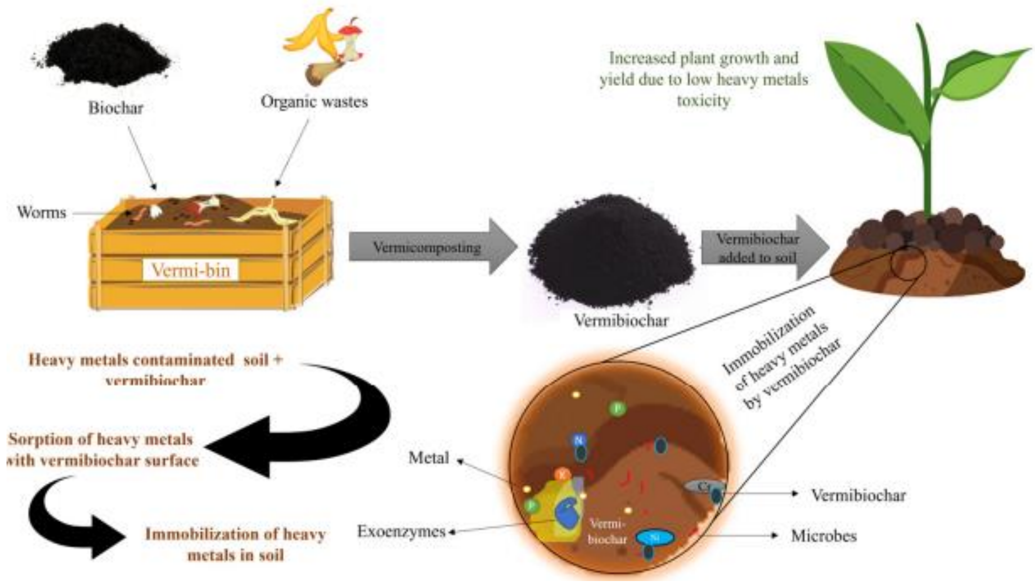

Figure 8. The combined potential of earthworms and biochar in the bioaccumulation and immobilization of HMs during the vermicomposting process and in HMs contaminated soil, respectively [26].

3.2.4. Effect on Pests and Diseases

Vermicompost plays a vital role in plant protection by suppressing a wide range of infectious diseases and plant-parasitic insects. Its extracts, when applied as foliar sprays, have been effective in reducing fungal infections in ornamental plants and crops, including diseases caused by *Phytophthora infestans*. Vermicompost significantly reduces the incidence of nematodes and other plant-parasitic organisms, likely through mechanisms such as competition, antibiosis, and parasitism. It also induces systemic resistance in plants, triggering the production of defense substances that further reduce disease occurrence. Additionally, vermicompost enhances the microbiological activity of potting media by enriching microbial diversity and lowering biomass accumulation in waste. The presence of beneficial microorganisms within vermicompost provides a natural defense against harmful pathogens, decreasing the reliance on chemical pesticides and supporting sustainable disease management [17].

3.2.5. Biochar Effects on Soil Greenhouse Gases

Greenhouse gases like CO_2, CH_4, and N_2O are key from both human and agricultural activities, including rice farming, fertilizer use, and livestock. Biochar can influence GHG emissions, but effects vary based on biomass type, pyrolysis conditions, soil type, and climate. Emissions from biochar-amended soils are controlled by soil properties like moisture, aeration, porosity, and organic matter, through both microbial (biotic) and chemical (abiotic) processes. However, responses are complex, soil and biochar-specific, and not yet fully understood [27, 28].

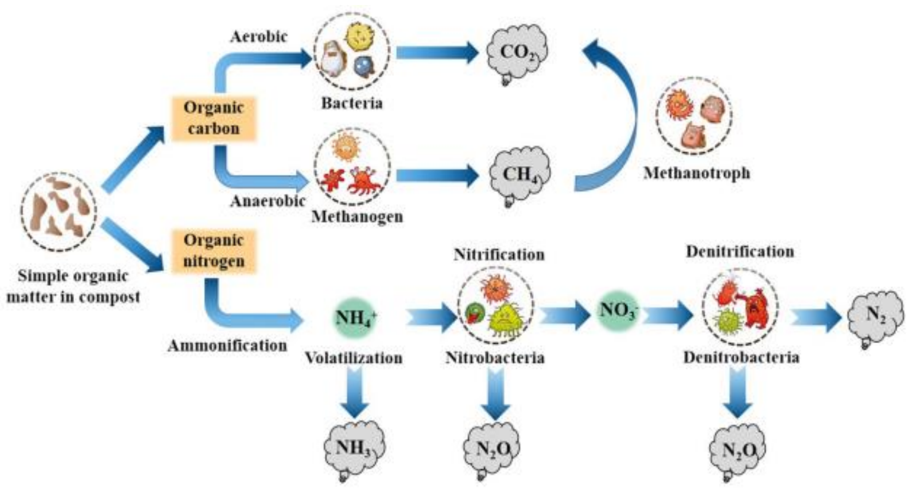

Figure 9. Flow chart of greenhouse gas emissions during composting [28].

The synergistic application of biochar and vermicompost provides complementary benefits that surpass the effects of using either amendment alone. Biochar enhances nutrient stabilization, water retention, and nutrient uptake through its porous structure, large surface area, and high cation exchange capacity, which increase nutrient adsorption and reduce leaching. At the same time, vermicompost enriches the soil with essential nutrients like nitrogen (N), phosphorus (P), and potassium (K), promotes beneficial microbial activity, aids in mineralization, and supports biological nitrogen fixation [29]. The combined use significantly improves soil structure, aeration, moisture content, and infiltration rates while reducing bulk density and dispersion ratio. Vermicompost provides labile organic matter and plant growth regulators, while biochar creates favorable habitats for microbial communities, enhancing microbial activity and enzyme functions. This integration leads to improved nutrient cycling, organic matter content, and soil organic carbon levels, buffering soil pH and reducing the need for synthetic fertilizers. Overall, the co-application of biochar and vermicompost has shown to be an effective strategy for boosting soil health, enhancing wheat growth and yield, and promoting sustainable agriculture [18, 24].

3.2.6. Biochar for Improving Water Use Efficiency (WUE)

With global warming intensifying and disrupting the hydro-climatic balance, water scarcity is expected to become more severe, leading to a growing gap between water supply and demand. In such water-limited conditions, soil amendments like biochar offer a promising solution. By improving soil structure, moisture retention, and nutrient availability, biochar can significantly enhance water use efficiency in agricultural systems, making them more resilient to climate-induced water stress [22].

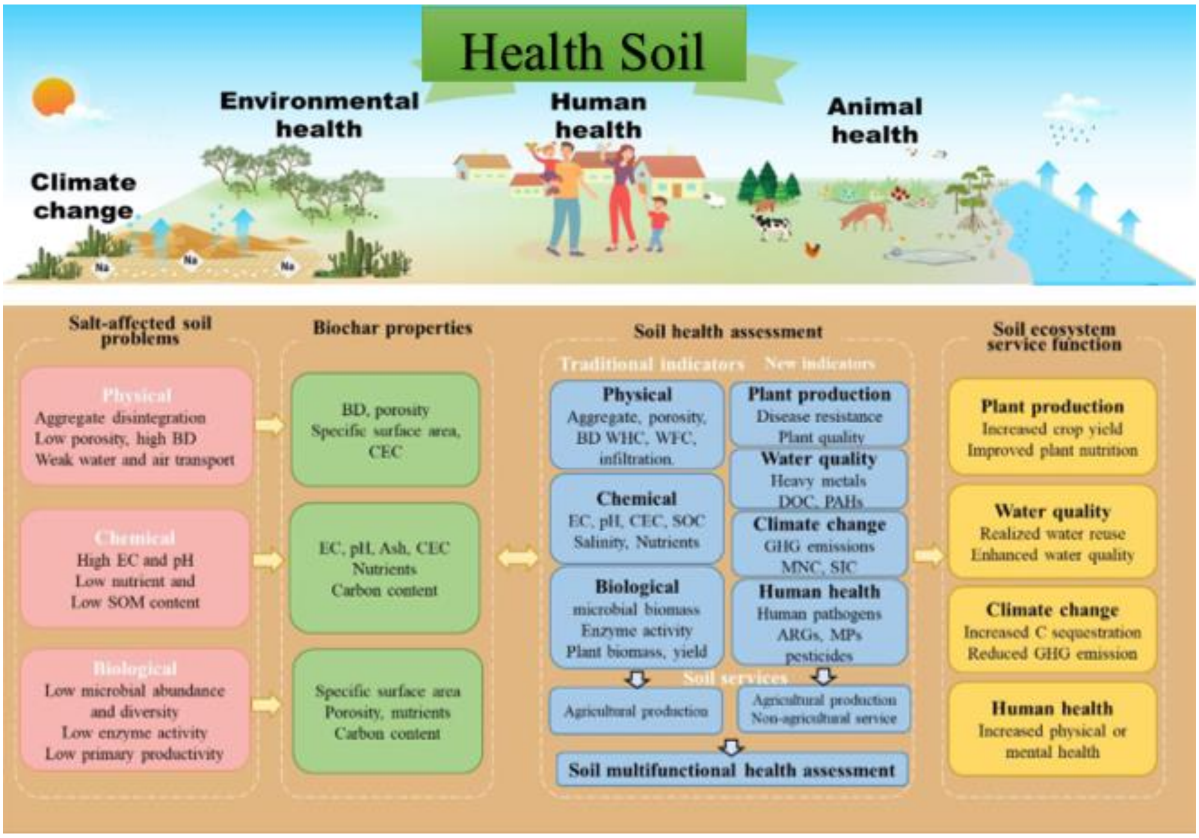

Figure 10. *Biochar mediated soil health and global-ecosystem service functions of salt-affected soils [21].*

4. Conclusion

The combined application of biochar and vermicompost presents a promising strategy for enhancing soil health and supporting sustainable management. Biochar improves key soil properties such as water retention, aeration, porosity, organic matter, and cation exchange capacity, while reducing nutrient leaching and greenhouse gas emissions like N_2O and CH_4. Vermicompost, produced through the biological activity of earthworms and microbes, contributes microbial life, plant growth hormones, and nutrient-rich organic matter that enhances both the physical and chemical quality of the soil.

Their synergistic use improves soil structure, nutrient availability, microbial activity, and water-holding capacity, leading to increased crop productivity, better seed germination, and stronger disease resistance. This integrated approach also helps reduce soil salinity and electrical conductivity through adsorption and ion exchange, making it effective for managing salt-affected soils.

Furthermore, the combination of biochar and vermicompost offers enhanced capacity for remediating soils contaminated with heavy metals such as cadmium, lead, and arsenic due to their ability to bind and immobilize toxic ions. Their complementary properties not only improve plant nutrient uptake and soil fertility but also contribute to sustainable organic waste recycling and carbon sequestration. This eco-friendly method supports long-term agricultural productivity while reducing environmental risks like desertification, contamination, and greenhouse gas emissions. The integrated use of biochar and vermicompost is a valuable tool for addressing soil degradation and ensuring the long-term viability of agricultural systems. Continued efforts and research are needed to refine these practices across diverse environments and crop systems for maximum impact in sustainable agriculture.

Abbreviations

SOM	Soil Organic Matter
BC	Biochar
CEC	Cation Exchange Capacity
WHC	Water Holding Capacity
WUE	Water Use Efficiency

Conflicts of Interest

There is No Conflicts of Interest.

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