



Category: Review

Organic Amendments as Tools for Soil and Environmental Restoration: A Review

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ABSTRACT

Soil degradation is considered as a serious limiting factor for agricultural production, the provision of ecosystem services, and environmental stewardship on a local, national, and global level. Organic amendments (OA) such as biochars, composts, vermicomposts, and animal manures are increasingly being considered as promising nature-based solutions for the restoration of degraded soils. However, an integrated approach to the topic of soil physicochemical restoration, heavy metal immobilization and GHG dynamics in a single framework still does not exist in the current literature. To bridge this gap, a systematic review was conducted using PRISMA guidelines, screened published from 2000 to 2024 in Web of Science, Scopus and Google Scholar and only 127 articles were included. This systematic review aims to critically analyze the latest scientific literature on the application of OA for the restoration of degraded soils, with a special focus on the implications for climate change mitigation. The results of these studies collectively show that OA can consistently increase soil organic carbon up to 40%, increase nutrient retention by up to 35%, and increase microbial biomass carbon by 20–60% compared to unamended soils. The soil aggregate stability was increased by 18–45% in soils of different textural classes. With heavy metal contaminated soils, biochar and compost application by 30–70% the bioavailability of lead, cadmium and arsenic by adsorption and complexation, pH elevation and microbial mediated mechanism. Climate regulation: Application of OA resulted in diverse responses in N₂O emissions (between -45 to +20%) and methane fluxes, highlighting that the responses in GHG to OA are context-dependent. This review, judicious incorporation of OA into the soil is a pragmatic approach to promote sustainable agriculture and environmental restoration. Further studies should be carried out with more emphasis on field experiments of longer duration, application of combined amendments, and region-specific guidelines for optimization of soil health and environmental performance at the global scale.

1. Introduction

Soil is considered an “irreplaceable” non-renewable resource that performs essential ecosystem functions, including nutrient cycling, water regulation, carbon sequestration, and food production [1]. However, during recent decades, intensive agricultural management, unbalanced fertilization, industrial activities, and climate change have substantially accelerated soil erosion worldwide. Soil degradation encompasses processes such as acidification, depletion of organic carbon, nutrient imbalance, salinization, and

contamination, ultimately reducing the soil's capacity to support plant growth and ecosystem-related functions [2].

Approximately one-third of global cropland is affected by soil degradation to varying degrees during last 40 years 24 billion tons of fertile soil lost due to erosion [3]. The decline in soil quality threatens the ability of agricultural systems to meet the food demands of a rapidly growing population, while the shrinking availability of arable land further

exacerbates this challenge. Conventional soil restoration methods, including chemical and physical treatments, are often expensive and may produce adverse effects on soil fertility and structure [4]. Therefore, the development of economically feasible and ecologically sustainable strategies for soil restoration and productivity enhancement has become imperative.

OA are increasingly recognized as nature-based solutions for addressing multiple dimensions of soil degradation. These amendments are derived from biological materials such as crop residues, animal manure, food waste, and other organic substrates. Their application contributes to the restoration of soil organic matter (SOM), improvement of soil structure, enhancement of nutrient availability, stimulation of microbial activity, and formation of long-term carbon sinks [3]. In addition, OA serve as effective waste management tools by converting organic wastes into valuable soil conditioners, thereby maintaining nutrient cycling within agricultural systems.

Recent studies have demonstrated the effectiveness of OA—particularly biochar, compost, and vermicompost, in the rehabilitation of various types of degraded soils. Biochar has been shown to immobilize heavy metals in contaminated soils while simultaneously improving soil water retention and nutrient availability [1,5]. Compost and vermicompost not only enhance soil carbon sequestration but also increase crop yields and reduce reliance on synthetic fertilizers [6,7,8]. Furthermore, the application of OA can mitigate greenhouse gas emissions from agricultural soils, thereby contributing to climate change adaptation and mitigation strategies [9].

The objective of this review is to provide a comprehensive synthesis of recent advances in OA and their roles in soil rehabilitation and environmental protection. The review discusses the types and characteristics of OA, their effects on the physical, chemical, and biological properties of soils, the mechanisms involved in the remediation of polluted soils, their contributions to carbon sequestration and climate change mitigation, and key factors influencing their field-scale application. Ultimately, this review aims to support sustainable soil management practices that enhance agricultural productivity while minimizing environmental impacts by consolidating current knowledge and identifying critical research gaps.

2. Soil Degradation: Causes, Impacts, and Global Scale

2.1 Soil Degradation Factors

Soil degradation results from multiple interrelated natural and anthropogenic drivers. Among these, agricultural practices are a major contributor account for approximately 30% of global soil degradation [43], particularly under intensified systems characterized by continuous monocropping, excessive tillage, and removal of crop residues, which collectively accelerate SOM depletion and structural deterioration [10]. Industrial pollution for contributes 10-15%, and climate change acts as a threat multiplier across all systems [44]. Improper fertilizer management further aggravates soil degradation by causing nutrient imbalances, acidification, and declines in biological activity [11]. In addition, heavy metals and organic pollutants originating from industrial activities enter soils through atmospheric deposition, waste water discharge, and improper waste disposal, posing long-term risks to ecosystems and human health [1].

Mining activities generate substrates with poor physical structure, low nutrient availability, and elevated concentrations of toxic elements, making land reclamation technically challenging and economically expensive [12]. Urbanization and construction disturb natural soil profiles, producing compacted soils with low organic matter content and limited fertility [13]. Climate change further intensifies soil degradation through rising temperatures, altered precipitation patterns, and an increased frequency of extreme weather events [14]. The degradation processes can be divided into three broad categories: physical degradation, chemical degradation, and biological degradation, with each category having different mechanisms but often overlapping.

2.1.1 Physical Degradation

Water and wind erosion are the most common types of physical degradation in the world with around 1,094 million hectares of soil degraded by water and wind erosion, with water erosion accounting for about 56% and wind erosion about 28% of the total degraded land area [45]. Deforestation, heavy tillage, and the clearance of crop residues are the main reasons for accelerated erosion, and all three of these practices have a negative impact on the aggregate stability of soils. Soils that are overgrazed or compacted (usually due to heavy agricultural machinery) can decrease soil porosity and hydraulic conductivity by up to 60–80% in especially compacted soils [46], which hinders infiltration and root growth.

2.1.2 Chemical Degradation

Chemical degradation encompasses acidification, salinization and contamination by toxic chemicals, and it impacts more than 1.5 billion

hectares of agricultural and non-agricultural lands globally [47]. Today, about 40–50% of the arable soils worldwide are acidified, mostly as a result of the excessive use of nitrogen-based fertilizers, acid deposition, and leaching out of base cations [48].

2.1.3 Biological Degradation

Biological degradation is the loss of soil organic matter (SOM), loss of microbial biodiversity and the inhibition of important soil functions critical for nutrient cycling and soil structure maintenance. In general, the intensification of agriculture is the main cause of biological degradation, with around 28–35% of the global soil degradation attributed to this [47]. These practices stimulate the decomposition of SOM by increasing its oxidation and decrease the inputs of organic C by the increased use of inorganic fertilizers, causing a net loss of about 30–50% of SOM compared to native soils after many years of intensive cultivation [49].

2.2 Consequences of Soil Degradation

The impacts of soil degradation extend beyond reduced agricultural productivity. Loss of SOM diminishes soil water-holding capacity and nutrient retention, increasing crop vulnerability to drought and nutrient stress [15]. Structurally degraded soils are more susceptible to erosion by wind and water, leading to further nutrient losses and reduced soil depth [16]. Declines in soil biological quality, reflected by reduced microbial diversity and abundance, impair nutrient cycling, organic matter decomposition, and biological regulation processes [17].

From an environmental perspective, soil degradation contributes to increased greenhouse gas emissions through the mineralization of SOM and subsequent release of carbon dioxide. Reduced soil buffering capacity also limits pollutant filtration, increasing the risk of water contamination through nutrient leaching and heavy-metal mobilization. Moreover, declining agricultural land availability promotes the conversion of forests and grasslands into cropland, exacerbating biodiversity loss and carbon emissions [4].

2.3 Global Range and Economic Repercussions

Soil degradation occurs on all continents but is particularly severe in densely populated developing regions where agricultural intensification is most pronounced. In China, large areas of degraded land resulting from urban expansion and land abandonment require rehabilitation to ensure national food security [18]. The environmental protection market in China is projected to exceed 4

trillion Chinese Yuan (CNY) by 2029, with soil rehabilitation representing a significant component [19]. Economics of Land Degradation (ELD) Initiative stated that the economic losses from global land degradation are estimated to be some USD 10.6 trillion per year, or around 17% of global GDP.

The economic consequences of soil degradation include reduced agricultural productivity, increased costs of soil restoration, expenses associated with water treatment to remove agricultural pollutants, and health-related costs linked to food-chain contamination. Conversely, investments in soil conservation and rehabilitation can yield substantial economic returns through improved crop yields, enhanced ecosystem services, and contributions to climate change mitigation [4]. Sub-Saharan Africa is one of the most heavily impacted regions, with an estimated 65% of agricultural land being deemed degraded and causing annual losses in crop yield in staple food systems of 8–25% [50]. The losses due to nutrient depletions alone are estimated to cost the economy of sub-Saharan Africa USD 4 to 8 billion annually from foregone agricultural production and increase rural poverty and food insecurity [50]. In South Asia, approximately 120 million hectares of degraded land are present in just India, resulting in an estimated productivity loss of USD 2.4 billion per year [51].

3. Properties and different types of OA

3.1 Biochar

Biochar is a carbon-rich, porous material produced through the pyrolysis of biomass under limited oxygen conditions at temperatures typically ranging from 300 to 700 °C [1]. Feed stocks for biochar production include agricultural residues (e.g., wheat straw, rice straw, and corn stover), wood, animal wastes, sewage sludge, and other organic materials. The effectiveness of biochar as a soil amendment depends largely on its physicochemical properties, which vary according to feed stock type and pyrolysis conditions. Biochar generally exhibits high specific surface area, well-developed porosity, abundant surface functional groups (e.g., carboxyl, hydroxyl, and carbonyl), high cation exchange capacity, and alkaline pH [20].

Feed stocks with high lignin content, such as wood and straw, influence biochar aromaticity and enhance its capacity to adsorb organic pollutants. In contrast, biochars derived from high-ash feed stocks, such as manure and sewage sludge, possess higher mineral contents and cation exchange capacities, which improve nutrient retention and heavy-metal immobilization [20]. The aromatic structure of biochar confers exceptional resistance to microbial decomposition, enabling it to

persist in soils for centuries to millennia and making it a valuable material for long-term carbon sequestration. By 2050, biochar application is estimated to contribute to reductions of up to 6.6 Pg CO₂-equivalent emissions annually [20].

3.2 Compost

Composting is an aerobic biological process involving the decomposition of organic materials by thermophilic microorganisms operating at temperatures of approximately 55–70 °C. This process stabilizes organic matter, eliminates pathogens and weed seeds, and converts nutrients into plant-available forms. Common compost feed stocks include animal manures, crop residues, food waste, yard trimmings, and municipal organic waste. Well-matured compost is characterized by a dark color, earthy odor, and crumbly texture. It contains balanced concentrations of macronutrients and micronutrients, along with humic substances that improve soil aggregation and water-holding capacity. The carbon-to-nitrogen ratio of mature compost typically ranges from 15:1 to 25:1, indicating a combination of immediate nutrient availability and slow-release nitrogen [21]. Compost application has been shown to increase SOM content by 20–35% compared with sole reliance on synthetic fertilizers, leading to improved soil structure, water infiltration, and nutrient retention [7]. Compost also enhances labile and stable organic carbon pools, supporting microbial activity and long-term carbon storage [7].

3.3 Vermicompost

Vermicompost is the stabilized end product of organic waste decomposition mediated by earthworms—primarily *Eisenia fetida* (red wigglers) and *Eudrilus eugeniae* under moderate temperature conditions (15–30 °C) that avoid thermal stress to the worms [21]. Unlike conventional composting, vermicomposting involves the simultaneous action of earthworm digestion and intense microbial activity, resulting in the rapid transformation of organic waste into nutrient-rich castings [21].

Vermicompost exhibits several distinctive properties compared with conventional compost. It contains higher concentrations of plant-available nutrients; particularly nitrogen, phosphorus, and potassium, derived from enhanced microbial mineralization during passage through the earthworm gut [22]. In addition, vermicompost is enriched with plant growth regulators such as auxins, gibberellins, and cytokinins, which stimulate root development and improve nutrient uptake efficiency [23]. The casting process further enriches vermicompost with beneficial microbial populations,

including nitrogen-fixing and phosphate-solubilizing microorganisms, as well as microbes capable of suppressing soil-borne plant pathogens.

Recent studies have demonstrated that vermicompost significantly enhances soil carbon sequestration through multiple mechanisms. Soils amended with vermicompost have shown increased abundance of carbon sequestration-related genes encoded by soil phages [8]. The average carbon sequestration potential of vermicompost-treated soils reached 65.18% compared with 50.21% in control soils [8]. Dominant temperate phages in vermicompost-amended soils encode glycosyltransferases that facilitate the conversion of low-molecular-weight organic compounds into stable, high-molecular-weight carbon forms resistant to degradation, thereby promoting long-term carbon storage.

3.4 Animal Manures

Animal manures, including cattle, poultry, swine, and sheep manures, have been used as soil amendments for centuries. These materials represent valuable sources of essential plant nutrients; however, proper composting or aging is required prior to application to minimize nitrogen losses, pathogen transmission, and phytotoxic effects. When appropriately processed, animal manures provide balanced nutrient supply, improve soil structure, and stimulate microbial activity [1].

Nutrient composition and carbon-to-nitrogen (C:N) ratios vary considerably among manure types. Poultry manure is characterized by high nitrogen content and low C:N ratio, resulting in rapid nutrient availability but comparatively limited long-term soil organic matter accumulation. In contrast, cattle and sheep manures contain higher fiber content and wider C:N ratios, contributing more effectively to soil structural improvement and long-term carbon sequestration [1].

4. Effects of OA on Soil Properties

4.1 Physical Properties

The incorporation of organic amendments significantly alters soil physical properties that govern water movement, aeration, root penetration, and resistance to erosion. Organic matter inputs promote soil aggregation through mechanisms such as microbial polysaccharide production, fungal hyphal binding, and stabilization by humified organic compounds [24].

Organic amendment application has been shown to markedly improve soil structure in degraded lands. Reclaimed soils treated with composted poultry manure exhibited enhanced aggregate

stability, reduced bulk density, and increased water infiltration compared with soils receiving only synthetic fertilizers [1]. Similarly, disturbed soils amended with biochar displayed increased porosity and water-holding capacity, with benefits persisting throughout the soil establishment period [25].

The porous structure of biochar physically protects soil organic matter by occluding it within aggregates, thereby reducing decomposition rates and enhancing long-term carbon storage [26]. Additionally, the alkaline nature of many biochars produces a liming effect that ameliorates soil acidity, particularly in degraded tropical soils and regions affected by acid deposition. Compost and vermicompost further contribute to improved soil crumb structure, creating favorable conditions for root growth and microbial activity and enhancing overall soil structural stability [27].

4.2 Chemical Properties

The application of OA causes notable changes in several soil chemical properties: pH, nutrient availability, cation exchange capacity, and salinity. The extent of these changes in some cases and sometimes even their direction will depend on soil amendment type, application rate, and initial soil conditions.

4.2.1 Soil pH and Salinity Management

Most OA, particularly biochar and mature compost, exhibit alkaline properties and can counteract soil acidification. Long-term chemical fertilization has been shown to decrease soil pH by 0.3–0.5 units per decade; however, this trend can be mitigated by organic inputs through the release of base cations such as calcium and magnesium [28]. While the liming effect of biochar is beneficial for acidic soils, excessive application may elevate soil pH beyond optimal levels and reduce micronutrient availability, highlighting the need for careful management [29].

4.2.2 Nutrient Enhancement

Long-term application of OA significantly increases soil nutrient pools. Combined use of organic and mineral fertilizers has been reported to increase alkaline hydrolyzable nitrogen by 18–22%, available phosphorus by 25–30%, and exchangeable potassium by 15–20% compared with sole chemical fertilization [30]. Although ammonium nitrogen release from OA occurs gradually, prolonged mineralization can increase available nitrogen by 32–35% [31].

The slow-release nature of nutrients from OA reduces leaching losses while ensuring sustained

nutrient supply throughout the crop growth cycle [32]. Vermicompost, in particular, provides balanced nutrient availability due to stabilization of organic nitrogen during earthworm gut passage, thereby minimizing volatilization losses while maintaining both readily available and slowly mineralizable nutrient fractions [22].

4.2.3 Cation Exchange Capacity

Enhancement of soil CEC through OA application improves nutrient retention and reduces fertilizer requirements. Carboxyl and phenolic functional groups present in humic substances provide negatively charged sites that retain essential cations such as calcium, magnesium, potassium, and ammonium, preventing their leaching. Biochars derived from high-ash feed stocks exhibit particularly high CEC values, substantially improving soil nutrient-holding capacity [33].

4.3 Biological Properties

4.3.1 Microbial Biomass and Activity

OA serve as both energy and nutrient sources for soil microorganisms, resulting in rapid increases in microbial biomass carbon and nitrogen. Amendments such as biochar, compost, and animal manures have been shown to significantly enhance microbial biomass in soils with low organic matter content [34]. The porous structure of biochar provides microorganisms with physical protection from predation and environmental stress while facilitating access to nutrients and water [35].

Long-term OA application consistently increases soil organic carbon levels, partly through stimulation of microbial activity [36,37]. The diverse microbial communities introduced with organic amendments perform essential ecological functions, including nitrogen fixation, phosphorus solubilization, and enhancement of plant productivity.

4.3.2 Microbial Community Composition

OA application shifts soil microbial communities toward copiotrophic bacteria that efficiently utilize labile organic substrates. Increased abundance of genes associated with carbohydrate and energy metabolism has been observed following organic fertilizer application, indicating enhanced metabolic activity and functional diversity [17,38]. In contrast, exclusive reliance on chemical fertilizers reduces the abundance of functional genes, leading to simplified microbial networks.

Vermicompost application exerts particularly strong positive effects on beneficial microbial populations. Increased bacterial richness and

dominance of temperate phages have been observed in vermicompost-treated soils [8]. These phages encode auxiliary metabolic genes involved in carbon conversion and storage, including glycosyltransferases that promote transformation of labile carbon into recalcitrant forms, thereby enhancing long-term carbon sequestration.

4.3.3 Enzyme Activities

Soil enzyme activities associated with key nutrient transformation processes increase markedly following organic amendment application. Enzymes such as β -glucosidase, phosphatase, urease, and dehydrogenase exhibit higher activities in amended soils and serve as indicators of microbial metabolic potential [38]. Elevated enzyme activity accelerates nutrient cycling and improves nutrient availability to plants.

Soil physicochemical properties, particularly pH and organic matter content, exert strong control over microbial functional gene abundance. Optimized combinations of organic and mineral fertilizers can effectively regulate these properties, promoting stable and functionally diverse soil microbial communities [39].

5. Role of OA in Soil Remediation

5.1 Heavy Metal Contamination

Heavy metal contamination of soils represents a critical environmental issue affecting ecosystem integrity and human health. Major sources include mining activities, industrial emissions, sewage sludge application, and the use of metal-containing agrochemicals. Heavy metals accumulated in soils can be taken up by plants and transferred through the food chain, causing severe health effects such as neurological disorders, kidney failure, and carcinogenic outcomes [1].

Table 1: Immobilization efficiency-% reduction in bioavailability

Amendment	Cd	Pb	Cu	Zn
Biochar	55-90	60-95	40-80	40-75
Compost	22-55	35-65	30-60	25-50
Vermicompost	25-50	30-60	25-55	20-45
Animal manure	10-35	20-45	15-40	15-35

5.1.1 Adsorption

Immobilization of heavy metals using organic amendments; particularly biochar has emerged as an effective in-situ remediation strategy. Biochar stabilizes metals through adsorption onto its extensive surface area and abundant functional groups. Coordination reactions between metal ions and surface carboxyl, hydroxyl, and carbonyl groups form stable complexes that reduce metal mobility

[20]. In addition, the micro-and mesoporous structure of biochar physically entraps metal ions, further limiting their availability in soil solution.

5.1.2 Ion Exchange

Negative surface charges on OA facilitate cation exchange processes, whereby weakly held cations such as calcium and magnesium are displaced by heavy metals. The high CEC of biochar and aged compost makes them particularly effective for metal immobilization through ion exchange mechanisms [19].

5.1.3 Precipitation

The alkaline pH of many OA promotes heavy metal precipitation as hydroxides, carbonates, or phosphates. Rice straw-derived biochar has been shown to effectively immobilize colloid-associated heavy metals by enhancing precipitation reactions. The high mineral content of biochar, particularly calcium, phosphorus, and iron-based oxides, provides nucleation sites that further reduce metal solubility and mobility in soils [5].

5.2 Organic Pollutant Remediation

Soils with organic contaminants (polycyclic aromatic hydrocarbons (PAHs), pesticides, petroleum hydrocarbons, and pharmaceuticals) are a global concern and it is estimated that 342,000 contaminated sites are identified in Europe alone that need immediate remediation [52]. The use of OA application promotes the growth of microbial communities that degrade hydrocarbons, which results in a faster biological degradation of recalcitrant organic compounds and increases the overall rate of in-situ bioremediation by 30 to 60% in contaminated soils compared to soils that are not amended with OA [53].

5.3 Soil Salinity and Sodicity Remediation

Salinization and sodicity, which are distributed across more than 1 billion hectares of soils globally, cause osmotic stress, ionic toxicity and dispersion of clay particles causing loss of soil structure that affect plant growth. The benefits of organic amendments to saline and sodic soils are provided in several ways: (1) by displacing and releasing salt from the exchangeable pool present in the soil; (2) by increasing the hydraulic conductivity of the soil to leach out salts; and (3) through promoting the growth of halotolerant microbes that enhance nutrient cycling under saline conditions [37]. In arid and semi-arid soils, application of biochar has been reported to significantly lower electrical conductivity of soil by 10–30%, and significantly improve the sodium adsorption ratio (SAR) of soil, while also

raising the growth of crop biomass by 15–45% in salt-affected soils [54].

6. Global Extent and Economic Implications

Soil degradation occurs on all continents but has highly adverse effects in the more populated developing countries that have emphasized the intensification of agriculture. In China alone, abandoned homesteads and construction have resulted in very large extents of degraded land that need to be treated to satisfy the need for food security [18]. The environmental protection industry in China is forecast to achieve sales above 4 trillion CNY by the end of 2029, with soil restoration expected to be a prominent sub-sector [19].

The economic impacts of degraded soils include losses in agricultural productivity, costs associated with soil restoration, expenditures for water purification to remove agricultural pollutants, and healthcare costs arising from pollutant transfer through the food chain. In contrast, investments in soil conservation and restoration generate substantial returns through increased productivity, enhanced ecosystem services, and climate change mitigation benefits [4].

6.1 Field Applications and Effectiveness

Recent field trials have confirmed the effectiveness of OA in remediating heavy metal contaminated soils. Wei et al., 2025 demonstrated that a combined treatment using heavy-metal-resistant bacteria and maize straw biochar achieved greater immobilization of lead and cadmium compared with individual amendments [40].

Similarly, biochars derived from bamboo and rice straw significantly reduced exchangeable heavy metal fractions while increasing residual metal pools in contaminated soils [30]. In mining-affected soils, integrated restoration approaches combining OA and phytoremediation have shown promising outcomes. The application of compost, biochar, and organic waste mixtures enhanced soil fertility, increased plant survival, improved water-holding capacity, and reduced metal toxicity in mine spoils [12].

6.2 Organic Pollution Remediation

Beyond heavy metals, OA are also effective in remediating soils contaminated with organic pollutants such as polycyclic aromatic hydrocarbons (PAHs), polychlorinated biphenyls (PCBs), pesticides, and petroleum hydrocarbons. Biochar exhibits strong adsorption capacity for these

compounds due to its aromatic structure and hydrophobic surface characteristics [1].

7. Carbon Sequestration and Climate Change Mitigation

7.1 Soil Carbon Sequestration

Soils constitute the largest terrestrial carbon reservoir, storing approximately three times more carbon than the atmosphere. Enhancing soil carbon sequestration is therefore recognized as a key strategy for climate change mitigation while simultaneously improving soil fertility and productivity.

7.1.1 Direct Carbon Addition

OA contribute directly to soil carbon inputs, ranging from labile fractions that decompose rapidly to highly recalcitrant carbon forms. Biochar represents the most stable carbon input, with turnover times ranging from centuries to millennia depending on feedstock and environmental conditions [1]. Compost and vermicompost contribute both labile and stabilized carbon fractions.

The application of cow-dung compost and vermicompost has been shown to significantly increase soil carbon content by enhancing labile organic carbon and residual oxidizable carbon pools, while maintaining crop yields comparable to chemical fertilizer treatments [7].

7.1.2 Stabilization in Aggregates

OA promote soil aggregation, thereby physically protecting soil organic matter from microbial decomposition. Carbon stored within aggregates is less accessible to enzymes and exhibits slower turnover rates. Vermicomposting further enhances carbon stabilization through earthworm casting, increasing the proportion of carbon stored in biogenic soil aggregates by up to 35% compared with untreated soils [41].

7.1.3 Priming Effect Modulation

Labile OA may induce either positive or negative priming effects on native soil organic matter. While short-term positive priming has been reported, long-term studies indicate net soil carbon accumulation following repeated organic amendment application, with outcomes dependent on amendment quality and decomposition dynamics [36].

7.2 Greenhouse Gas Emissions

Agricultural soils are major sources of nitrous oxide (N₂O) and methane (CH₄), which possess global warming potentials 273 and -27-30 times greater than carbon dioxide, respectively over a 100-year time horizon [55]. OA influence greenhouse gas

emissions primarily through modifications in soil aeration, nutrient availability, and microbial activity.

7.2.1 Nitrous Oxide Emissions

Nitrous oxide emissions arise mainly from nitrification and denitrification processes. OA can alter these pathways and significantly influence emission rates [6]. Field studies have reported reductions of approximately 20 ± 7 kg CO₂-eq ha⁻¹ yr⁻¹ following the application of ground rock and biochar amendments, largely due to increased soil pH suppressing nitrification and denitrification processes [12].

Though, the effects of OA on N₂O emissions are highly variable and depend on nitrogen content, decomposition rate, and interactions with mineral fertilizers. Fresh manure composts may increase N₂O emissions, whereas well-aged composts with optimal C:N ratios tend to reduce emissions through improved nitrogen use efficiency [9].

7.2.2 Methane Oxidation

OA can enhance methane oxidation in soils by improving habitat conditions for methanotrophic bacteria. Ground rock and biochar applications have been shown to significantly increase CH₄ oxidation rates in rangeland soils, contributing to overall greenhouse gas mitigation [42].

7.2.3 Carbon Dioxide Fluxes

Although OA may initially increase CO₂ emissions due to decomposition of labile carbon fractions, long-term effects generally favor net carbon sequestration when stable carbon inputs such as biochar are considered. Biochar amendments are associated with low CO₂ emissions and long-term carbon storage [1].

7.3 Climate Mitigation Potential

Large-scale adoption of OA has considerable potential to contribute to greenhouse gas mitigation targets. Up scaling scenarios indicate that combined applications of compost, biochar, and mineral amendments across rangelands could achieve reductions of up to 51.7 ± 14.9 Mt CO₂-eq yr⁻¹ through enhanced carbon sequestration and reduced N₂O and CH₄ emissions [9].

Beyond direct sequestration effects, OA indirectly mitigate climate change by reducing reliance on energy-intensive synthetic fertilizers, limiting agricultural land expansion, and enhancing soil resilience to climate extremes. Nevertheless, trade-offs such as emissions during amendment production, transport, and nutrient losses must be carefully managed.

8. Challenges and Future Research Directions

8.1 Knowledge Gap

Despite considerable scientific investigation on OA, several evidence gaps remain. The long-term stability and degradation processes of biochar across different soil types and climatic conditions have not yet been fully elucidated, particularly in tropical environments. Another major gap concerns the interactive effects of combined OA, which remain insufficiently explored under field conditions.

A deeper understanding of the mechanisms governing microbial community responses to OA requires advanced molecular-level analyses. The role of phage auxiliary metabolic genes in enhancing soil carbon sequestration has been highlighted in recent studies; however, the universality of these mechanisms across soil ecosystems has not yet been established [39]. In addition, the contributions of soil fauna other than earthworms to organic matter transformation and stabilization remain poorly understood and warrant further investigation.

8.2 Standardization and Scaling

Standardization of OA production processes, quality assessment protocols, and application methodologies is essential to improve comparability across studies and enhance the predictability of field-scale outcomes. Integrative process-based models that incorporate OA properties, soil characteristics, climatic variables, and management practices could significantly improve decision-support tools for growers [19].

Scaling up application rates from experimental plots to landscape or regional levels presents considerable logistical and technical challenges. The development of efficient infrastructure for the collection, processing, storage, and distribution of organic materials will require coordinated efforts among farmers, local authorities, industries, and policymakers to ensure sustainable implementation.

8.3 Climate Change Adaptation

In this regard, OA can play important roles in improving the resistance of soils to environmental stresses such as drought, high temperatures, floods, and saline soils. Further researches need to be conducted to determine the means by which different types of OA can improve the retention of water, the ability to regulate soil temperatures, and the stability of soils during adverse climatic conditions. The role of OA in climate-resilient agriculture remains important.

9. Conclusion

OA offer promising ecologically friendly solutions for purifying degraded soils and supporting environmental conservation. Available data already demonstrate significant beneficial effects for biochars, composts, vermicomposts, and heat-treated organic wastes on improving the physical, chemical, and biological properties of soils, while realizing various environmental aims such as carbon sequestration, greenhouse gas reduction, and contaminant immobilization. The processes that manage OA function are understood in greater detail and include direct C addition, aggregate stabilization, nutrient retention, microbiota stimulation, and contaminant sorption/precipitation. More recent developments in molecular approaches have clarified important roles of functional microbial genes and auxiliary phage-derived metabolic genes in carbon transformation and sequestration processes and provided new directions for the optimization of amendment functions through micro biome modification. Large-scale field applications under varied soil types and environmental conditions have confirmed the efficacy of OA for managing various types of degradation such as organic matter decline, nutrient deficiencies, compaction, acidic, saline, and toxic metal conditions. The use of OA in combination with residual and complementary management practices would prove more effective.

Despite the progress made, current difficulties lie in the standardization of the production and quality of the amendment, the scaling up of the application of the amendment from the laboratory to the real world, optimizing the mix of different kinds of amendments, and the deployment of supportive policies. Future efforts should be directed toward the evaluation of the amendment's retention in the field in the long run, the molecular analysis of the effect of the amendment on the microbial community in the soil, decision support systems, and climate change adaptation. The mass implementation of OA technologies can significantly address sustainable development outcomes in climate action, food security, and ecosystem rehabilitation aspects.

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