The Role of Organic Amendments and Their Impact on Soil Restoration: A Review

ABSTRACT

Soil organic matter (SOM) plays a pivotal role in maintaining soil health by enhancing its physical, chemical, and biological properties. It improves soil structure, water retention, nutrient availability, and microbial activity, contributing significantly to sustainable agriculture. Organic amendments, including animal manure, compost, biosolids, crop residues, and various organic by-products, are widely used to restore degraded soils by increasing SOM content. These amendments not only supply essential nutrients but also promote biological aggregation, suppress soil-borne pathogens, and improve soil's resistance to environmental stressors such as drought and heavy metal toxicity. The positive impacts of organic amendments on soil properties are well-documented, with key benefits including increased soil organic carbon (SOC), improved nutrient cycling, enhanced microbial diversity, and greater water-holding capacity. Organic materials such as compost and animal manure have been shown to significantly improve soil fertility and restore degraded soils. The application of green manure and crop residues also boosts soil biodiversity, enhances rhizospheric processes, and supports overall ecosystem resilience. This paper emphasizes the importance of adopting holistic soil management practices that include organic amendments, conservation tillage, and sustainable cropping systems to address soil degradation. By focusing on replenishing SOM, improving nutrient availability, and increasing soil biodiversity, these practices can contribute to the long-term sustainability of agricultural systems and environmental health. The restoration of soil organic matter is essential for enhancing soil quality and mitigating degradation, ultimately ensuring food security and ecosystem stability for future generations.

Keywords: Amendments, Soil restoration, Soil properties, Agriculture, Soil fertility, Organic manure,

1. INTRODUCTION

Human activities have profoundly altered Earth's ecosystems, leading to significant environmental degradation, particularly through changes to soil properties. Anthropogenic influences, such as agricultural practices, industrial development, and urban expansion, have resulted in the deterioration of soil's physical, chemical, and biological integrity. For instance, Ellis et al. [1] estimated that in 1700, 95% of Earth's ice-free land was categorized as wild or semi-natural landscapes. However, by 2000, human activities had transformed 55% of this land into rangelands, croplands, and urbanized areas, leaving only 45% of natural habitats intact. This shift not only reduces biodiversity but also disrupts soil ecosystems. Zika and Erb[2] reported that dryland degradation alone leads to the loss of 2% of global terrestrial net primary productivity annually, further diminishing soil quality.Without organic matter, the soil's ability to retain water, regulate temperature, and support microbial activity is significantly compromised. This creates a cycle of degradation that hinders future regeneration, making it increasingly difficult to restore degraded soils for productive use. Given the importance of soil organic matter for soil health, restoring degraded lands often hinges on rebuilding a surface horizon rich in organic matter. While importing topsoil is an option, it is often economically and environmentally unsustainable, as the donor areas themselves suffer degradation [3]. As an alternative, the use of organic amendmentssuch as manure, biosolids, and other organic wasteshas been practiced for centuries to restore soil fertility [4]. These materials help replenish soil organic matter and improve soil structure, nutrient content, and biological activity [5]. However, despite the well-documented benefits of organic amendments [6], they are often viewed with skepticism due to concerns about potential contaminants, such as heavy metals, pathogens, and excess nutrients, which can leach into water sources [7]. This paper explores the critical role of organic matter in soil restoration, examining how organic amendments can enhance soil properties and contribute to the recovery of degraded lands.

2 SOIL ORGANIC AMENDMENTS

Organic matter plays a crucial role in maintaining the health and functionality of soil ecosystems. It provides the essential substrates for decomposing microbes, which in turn release nutrients that plants require for growth. Furthermore, organic matter enhances soil structure, improves water-holding capacity, increases natural resistance to soil-borne pathogens, and mitigates the toxicity of heavy metals [8, 9]. Given these critical functions, restoring depleted organic matter levels in soil is a vital aspect of soil management. The application of organic amendments, such as compost, has proven to be an effective strategy for improving both the physical structure and the chemical and biological fertility of soils, as well as for suppressing soil-borne diseases [10, 11].The use of organic amendments to enhance soil fertility dates back thousands of years. Ancient civilizations, including the Greeks and Romans, recognized the benefits of applying animal manure and human sewage to soils, as well as the advantages of rotating crops with legumes to improve soil fertility [12]. Modern organic amendments include a variety of materials such as compost, animal manure, peat moss, wood chips, straw, sewage sludge, and sawdust, which can be categorized into five main types [12].

2.2 Types of Organic Amendments

2.2.1 Animal Manure

Animal manure, composed of a mixture of animal feces, urine, and bedding material, has long been used to improve soil fertility. Manure is derived from various livestock, including cattle, poultry, and pigs, and its nutrient content depends on the type of animal, the duration of storage, and whether the manure has been composted. Manure provides not only essential nutrients for plants but also organic matter that enhances soil structure and fertility. During aerobic decomposition, manure releases carbon dioxide and more stable organic compounds, while anaerobic conditions can produce methane and volatile organic acids [12].Animal manure is a primary source of organic fertilizer in agriculture, predominantly sourced from poultry, pig, cattle, and sheep farms [13]. With increasing food demand and shifts in human lifestyle and dietary habits, animal production has expanded significantly in recent years. This growth in the production of meat, eggs, dairy, and leather has introduced several new environmental challenges [14].

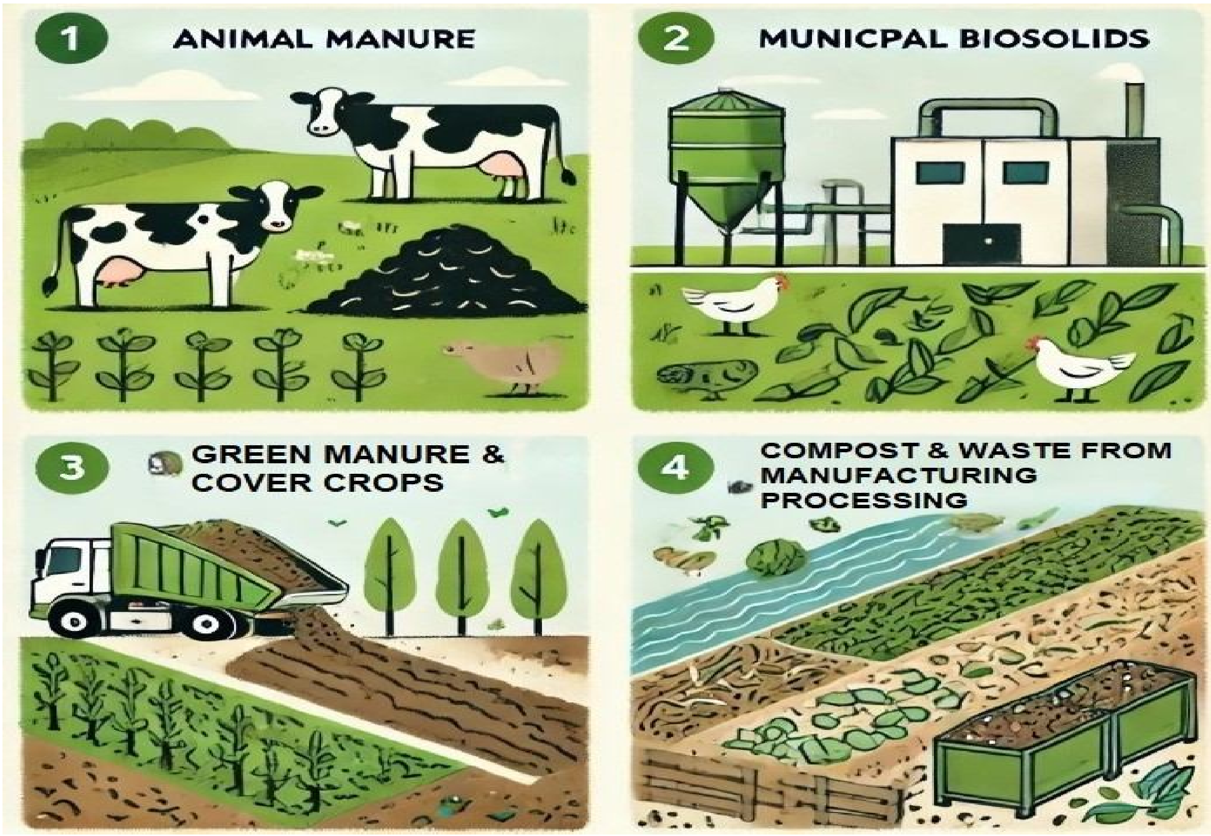

Figure 1: Illustration of Organic Amendment Types

Source: Author's Creation

2.2.2 Municipal Biosolids

Changing lifestyles have led to a global increase in wastewater production. As a result, biosolids which are residual byproducts from the treatment of municipal wastewater are also commonly applied to soil as fertilizer [15, 16]. Municipal biosolids, or treated sewage sludge, are organic materials processed to reduce odors and pathogens, making them suitable for agricultural use. Biosolids are rich in nutrients and organic matter but are subject to strict regulations to control levels of heavy metals, pathogens, and other contaminants before being applied to soils [12].

2.2.3 Green Manure and Cover Crops

Green manure involves growing specific crops and incorporating them into the soil while still green, which boosts soil fertility by adding organic matter and nutrients. Cover crops, such as legumes or non-leguminous species like sorghum and buckwheat, are used to protect soil from erosion and improve soil health during fallow periods or between crop rotations. Legumes are particularly beneficial as they fix nitrogen from the atmosphere, enriching the soil with both nitrogen and organic matter [12]. Cover crops can also increase microbial activity, improve water retention, and reduce erosion during off-season periods [17].

2.4 Compost and Waste from Manufacturing Processes

In recent years, compost has gained attention as an alternative to synthetic fungicides for controlling phytopathogens. Research shows that the increase in microbial biomass following compost application can lead to general disease suppression [18]. Composting is widely regarded as the most common method for recovering materials from organic waste. Composts are composed of a stable mixture of decayed organo-mineral materials derived from sources such as food scraps, green waste, animal manure, and sewage sludge [19]. In Europe, nearly half of the compost produced is applied to agricultural land [20]. Beyond enhancing soil organic carbon content, compost application has been shown to increase the abundance, activity, and biodiversity of soil microbiota [21]. Additionally, compost made from crop residues and green wastesuch as leaves, stalks, and stubblehas been found to improve soil water retention, significantly alter microbial communities, and help suppress plant diseases [22]. However, there are potential downsides to compost use. High electrical conductivity and a high carbon-to-nitrogen (C/N) ratio can lead to soil salinity and nitrogen immobilization. Compost derived from the organic fraction of municipal waste often contains elevated levels of heavy metals, which can accumulate in the soil with repeated use, posing environmental risks [23]. The presence of both organic and inorganic contaminants in compost, depending on its source, can therefore threaten agricultural systems (Kobayashi *et al.,* 2009). While decades of research on composting have yielded extensive knowledge about the process and its effects on soil [24], concerns about contaminants remain.

Meta-analyses have also demonstrated varying degrees of effectiveness in disease suppression depending on the type of phytopathogen [25]. However, the wide variability in compost quality, maturity, organic matter content, and microbial composition often results in inconsistent outcomes, making it difficult to identify specific indicators of pathogen suppression [26]. Compost is one of the most widely used organic amendments and is created through the controlled decomposition of organic waste materials. It provides multiple benefits, including the recycling of nutrients, improving soil organic carbon content, enhancing microbial activity, and supplying essential nutrients such as nitrogen, phosphorus, potassium, and magnesium [27]. Compost also improves soil porosity, water retention, and cation exchange capacity (CEC), while promoting the suppression of soil-borne pathogens such as *Pythium*, *Phytophthora*, and *Fusarium* spp. [28]. In recent years, on-farm composting has gained popularity as an environmentally friendly and cost-effective method for recycling agricultural waste into high-quality soil amendments [29]. This practice not only reduces waste disposal costs but also provides a sustainable source of compost for farmers, contributing to soil health and fertility. On the other hand, organic by-products from various manufacturing industries, such as seed residues, animal feathers, biochar, and paper mill biosolids, are increasingly being used as soil amendments. However, these materials are used less frequently in agriculture due to limited knowledge about their decomposition rates and nutrient availability [12].

3. Sources of Organic Amendments for Soil Restoration

A wide range of organic amendments is available for soil restoration, originating from agriculture, forestry, and urban waste streams. These materials provide essential organic matter and nutrients that help rehabilitate degraded soils, improving both their fertility and structure. Agricultural sources of organic amendments are among the most prevalent and include livestock manurewhether fresh, composted, or derived from solid fractions of anaerobic digestersproduced by cattle, hogs, and poultry. Crop residues, such as straw and leguminous plants, and spent mushroom compost are also commonly used. These amendments supply organic matter and nutrients that are vital for restoring soil health. Forestry also contributes organic amendments, including wood chips, shavings, and deinking sludge. In the past, wood residuals from the lumber industry were often incinerated to produce wood ash, which was also used as a soil amendment [30]. However, these forestry by-products are particularly useful for improving soil structure and increasing organic matter content in degraded lands.

Urban waste streams provide additional sources of organic amendments, such as biosolids (sewage sludge and municipal sludge) produced by wastewater treatment plants. The biodegradable fraction of municipal solid waste, which includes food scraps, yard waste, and paper products, is increasingly used in land restoration as well. These materials, previously destined for landfills, are now being diverted for agricultural use due to concerns over diminishing landfill space [21]. The food processing industry, which handles vegetables, grains, meat, and fish, generates significant amounts of organic by-products that could be used for soil restoration, although they are not yet widely utilized in this context [31]. Historically, organic amendments from urban areas, such as biosolids and food processing waste, were sent to landfills, but this practice has decreased in favor of land application as environmental concerns over landfill space have grown [32].

4. Effects of Organic Amendments on Soil Properties

Organic amendments significantly impact soil properties, both directly through their inherent characteristics and indirectly by modifying the soil's physical, biological, and chemical attributes. These amendments play a crucial role in soil restoration, particularly in degraded environments, where they enhance soil health, nutrient availability, and structure. Organic matter is essential for soil health and plays a critical role in maintaining overall environmental quality [33]. Intensive agricultural practices, when not supplemented with organic amendments to restore soil organic carbon, along with industrial pollution, can adversely affect the soil's chemical properties. This depletion of soil carbon content has harmful effects on microbial activity, diversity, and enzymatic functions [34]. Additionally, these practices can lead to a significant increase in soil salinity [35]. It is well established that adding organic amendments to soil increases soil organic matter, which in turn enhances water-holding capacity, porosity, and aggregate stabilitykey factors in improving soil quality [36]. Additionally, applying other waste materials such as rice husk, wheat straw, reeds, and biochar, alongside composts and manures, has been shown to improve soil aggregate stability and reduce bulk density [37]. Since organic fertilizers have a much higher water-holding capacity compared to degraded soils, their application can significantly boost the soil's water retention. This mixed approach to soil supplementation can amplify the benefits of organic amendments. However, the overall impact and long-term effects depend heavily on the type and number of organic amendments used [37, 38].

4.1. Soil Organic Matter Content

Soil organic matter is considered one of the most vital components influencing soil quality and functionality [39]. The application of organic amendments typically results in an immediate increase in soil organic carbon, with the amount of carbon added often proportional to the quantity of organic matter applied [40]. However, detecting measurable changes in soil organic carbon can be challenging, especially in soils with high background organic carbon or variability. The long-term retention of soil organic carbon depends on the rate of decomposition and the intrinsic quality of the organic amendment [41, 42]. Carbon introduced into the soil through organic amendments originates from plant material, with its stability influenced by factors such as plant type and post-harvest processing. For example, cereal straw incorporated into soil as part of manure decomposes differently than fresh straw, as composting stabilizes the carbon, leading to more durable improvements in soil organic matter [42].

4.2. Soil Microbial Communities

It is widely understood that after adding organic amendments to soil, the introduced microbial communities usually give way to the native soil microbes, except for some persistent pathogens [67]. The changes in soil microbial communities that follow are mainly linked to the shifts in the soil's physical and chemical properties caused by the amendments [14]. Organic amendments can alter the composition, biomass, and activity of native microbes by providing them with more nutrients for growth [21]. However, research on this topic often shows site-specific results. For instance, some studies have found no changes in microbial communities in soils contaminated with lead after adding organic materials like poultry litter, sheep manure, paper mill sludge, or cow slurry, possibly due to the severe contamination [43]. On the other hand, other studies have shown beneficial effects of organic amendments on native microbiota in agricultural soils [14]. In degraded soils, adding organic amendments has been found to boost soil life both in terms of quantity and biodiversity [44]. For example, animal manure has been shown to increase earthworm populations compared to soils only treated with synthetic fertilizers, likely due to the added carbon and improved water retention from organic fertilizers [45]. Organic amendments positively influence soil biota, enhancing soil biochemical activities such as enzymatic function and overall biodiversity [46]. Studies have shown that organic amendments, particularly animal manure, increase the abundance of earthworms compared to inorganic fertilizers [47]. The composition of the amendment also matters; farmyard manure and cattle slurry, for instance, tend to support higher earthworm populations than composts, due to the greater availability of carbon in manure. Similarly, microbial communities benefit from organic amendments, as they provide a significant carbon source that stimulates microbial growth and activity. This is often measured by the increase in soil microbial biomass carbon following the addition of organic amendments [48]. The level of microbial activity, however, varies depending on the decomposability and rate of application of the amendments [49].

4.3. Biological Aggregation and Soil Restoration

Organic amendments initiate soil biological activity, which plays a central role in soil reclamation. This process takes place in the detritusphere, a localized area around decomposing organic residues, where intense microbial activity occurs [50]. Studies have shown that decomposing plant residues significantly alter the physical structure of soil, promoting the formation of stable soil aggregates. As organic residues are colonized by microbes, they bind with mineral particles, creating stable aggregates that protect organic matter from rapid decomposition [51]. The application of organic amendments such as wood-derived sludge, compost, and cattle manure has been shown to promote the formation of soil aggregates, stabilizing soil organic carbon and contributing to the early stages of soil formation in highly degraded areas [52].

4.4 Nitrogen and Phosphorus Availability

Organic amendments or fertilizers contain varying amounts of nitrogen and phosphorus in different forms [53]. Organic amendments contain nitrogen in varying concentrations, with some forms more readily available than others [68]. Nitrogen is typically found in an organic form, but in animal manures especially liquid ones most of the nitrogen is in a mineral form that is readily available for plants to absorb [19]. When nitrogen is present in its organic form, it must undergo a process called mineralization to be converted into a form that plants can use [54]. One of the main advantages of using organic amendments instead of synthetic fertilizers is the different ways in which phosphorus becomes available. Studies have shown that applying animal manure is often more effective than using inorganic phosphorus fertilizers, leading to greater phosphorus availability. In contrast, the increase in phosphorus from synthetic fertilizers is often minimal, even with high application rates [55, 56]. In liquid animal manures, nitrogen is present in a mineral form (ammonia), which plants can absorb immediately [40]. However, in most organic amendments, nitrogen is in an organic form, requiring mineralization to convert it into a plant-available form. Low-nitrogen amendments may even immobilize nitrogen, competing with plants for available nitrogen. Predicting nitrogen availability from organic amendments depends on their chemical composition, including factors such as soluble cellulose and lignin-like fractions, which influence the rate of nitrogen mineralization [42].

4.5. Water-Holding Capacity and Plant-Available Water

Organic amendments typically increase the water-holding capacity of soils, particularly in sandy, degraded soils that lack this essential property [57]. The organic matter in these amendments absorbs and retains water, providing more plant-available water. The extent of this benefit depends on the type and decomposition state of the organic amendment. While some studies have shown significant increases in water retention following the addition of organic matter, the effects can vary depending on the soil texture and other factors [58].For instance, biosolids have been found to improve water retention in fine-textured soils such as silt loams but have less effect on sandy soils, where decreased bulk density may offset water retention gains [59]. Similar results have been observed with manure applications, which tend to increase water retention primarily due to the water absorbed by the organic matter itself [60].

Table 1: Positive Impacts of Soil Organic Amendments

Positive Impact	Details/Description	References
Increases Soil Organic Matter	Organic amendments increase soil organic carbon, which improves overall soil quality and functioning.	Gregorich *et al.,* [39]; Chantigny*et al.,* [40]; Lashermes*et al.,* [42]
Enhances Soil Structure	Organic matter improves poor soil physical conditions, leading to better structure and reduced compaction.	Viaud *et al.,* [41]; Golchin *et al.,* [51]; Sere *et al.,* [52]
Boosts Microbial Activity	Organic amendments provide carbon, which serves as an energy source for soil microbes, increasing microbial biomass.	Viaud *et al.,* [41]; Belyaeva & Haynes, [48]
Increases Soil Biota	Organic amendments, particularly animal manure, increase earthworm abundance and soil biodiversity.	Bastida *et al.,* [46]; Leroy *et al.,* [47]
Promotes Biological Aggregation	Induces biological activity that forms stable soil aggregates, protecting organic matter and contributing to pedogenesis.	Gaillard *et al.,* [50]; Golchin *et al.,* [51]; Sere *et al.,*[52]

Positive Impact	Details/Description	References
Improves Nitrogen Availability	Organic amendments can provide slow-release nitrogen, reducing the risk of leaching and enhancing plant uptake.	Chantigny*et al.,* [40]; Lashermes*et al.,* [66]
Increases Water-Holding Capacity	Organic matter retains more water, enhancing water-holding capacity, particularly in sandy and degraded soils.	Camberato *et al.,* [57]; Fierro *et al.,* [58]; Larney & Pan[3]
Suppresses Soil-Borne Pathogens	Compost amendments have been shown to suppress diseases caused by soil pathogens like *Pythium* and *Phytophthora*.	Borrero *et al.,* [28]; Donn *et al.,* [61]
Enhances Cation Exchange Capacity (CEC)	Compost improves soil CEC, increasing the soil's ability to retain and exchange nutrients.	Scotti *et al.,* [10]
Promotes Long-Term Carbon Stability	Composted materials stabilize carbon, resulting in longer-lasting increases in soil organic matter.	Lashermes*et al.,* [42]
Reduces Heavy Metal Toxicity	Organic matter can help mitigate the harmful effects of heavy metals in soil.	Park *et al.,* [9]

Source: Author's Compilation

In general, organic amendments play a critical role in improving soil properties, from increasing organic matter and microbial activity to enhancing water retention and nutrient availability. These changes support soil restoration, particularly in degraded environments, by creating conditions that promote long-term soil health and productivity. More so, organic amendments for soil restoration come from diverse sources, including agriculture, forestry, and urban waste. Each type of amendment offers unique benefits for improving soil quality, adding organic matter, and enhancing nutrient availability, all of which are critical for the successful rehabilitation of degraded soils.

5. Potential Risks of Organic Amendments

1. Application of sewage sludge and animal manures can introduce pathogenic microorganisms (e.g., *Escherichia coli*, *Salmonella*, *Campylobacter*, *Yersinia*), posing risks to soil health [61].

2. Organic amendments may contain heavy metals, which can accumulate in the soil especially when they are been slowly released over time.

3. The application of sewage sludge contributes significantly to microplastic contamination in soils (120 to 860 tons annually in Europe) [62]. Microplastics and nanoplastics have toxic effects on various organisms, including microbial communities, earthworms, birds, and mammals, raising concerns about ecosystem health [61, 63].

4. Organic amendments decompose over time, releasing bound contaminants such as metals and micro/nanoplastics, potentially affecting plant growth [64].

5. Contaminants from organic amendments can transfer through the food chain, impacting animal and human health [64].

6. CONCLUSION

Soil organic matter (SOM) is vital for soil health, affecting its physical, chemical, and biological properties. Effective SOM management supports soil fertility, sustainable agriculture, and ecosystem health. However, practices like continuous cropping and poor soil management deplete soil organic carbon (SOC), impacting soil structure, water retention, and productivity. Organic amendments such as manure, compost, and biosolids help restore SOC, improve soil structure, boost microbial activity, and enhance nutrient cycling. They also mitigate contamination risks but must be used cautiously to avoid releasing harmful substances. Integrating organic amendments with sustainable practices like conservation tillage and crop rotations is key to restoring soil health and ensuring long-term agricultural sustainability.

Conflict of interest

The authors declare no conflict of interest for this article.

Disclaimer (Artificial Intelligence)

Author(s) hereby declares that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of manuscripts.

Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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