# Challenges in Sustainable Agriculture—The Role of Organic Amendments

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Review

# Challenges in Sustainable Agriculture—The Role of Organic Amendments

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**Abstract:** Soil degradation threatens global food security and environmental sustainability, necessitating effective soil management strategies. This review comprehensively examines the impact of organic soil amendments on soil quality and productivity across various soil types and climatic conditions. A review of significant research related to organic amendments was performed using encompassed data from online search engines for studies published up until 31 December 2023. Despite their heterogeneity and use of varying methodologies, the data were narratively synthesized, providing a comprehensive understanding of amendment-induced changes in the chemical and physical properties of soil and the effectiveness of restoration on soil degradation. Organic amendments, including compost, vermicompost, biochar, and pomace, are pivotal in enhancing soil quality by increasing soil organic matter content, fostering aggregate formation, and improving soil structure in the short term. They positively influence water retention capacity, pH levels, nutrient availability, and carbon sequestration. In several studies, amendment-induced changes were absent, indicating that the effects of amendments vary depending on soil texture, application rates, and cropping systems, which emphasizes the need for tailored, sustainable soil management practices. This study concludes that organic amendments are a promising option for structure improvement and organic matter accumulation. It further suggests that an approach that integrates various methods is essential in order to meet desirable soil quality and retain agricultural productivity and offers valuable insights and recommendations for policymakers, practitioners, and researchers. Organic amendments can improve soil ecosystem services and contribute to climate change adaptation. In the future, more attention should be directed to tillage management and soil amendment interaction, as well as their effectiveness over specific periods of time.

**Keywords:** soil amendments; soil texture; organic matter; soil degradation

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## 1. Background

Soil is an essential natural resource that is necessary for sustainable Earth life [1]. Soils provide us with numerous regulating (e.g., air and water purification), provisioning (e.g., food), and cultural (e.g., recreation) ecosystem services, ensuring human well-being and sustainable socioeconomic development [2]. From the perspective of food demand and climate change, soil provisioning (food, water, raw material, medicinal resources, genetic resources, etc.) and regulating (climate regulation, erosion prevention, etc.) ecosystem services are a main focus of the scientific community [3–6].

Rising population growth and global warming are two of the most critical challenges that currently affect food supply security [7]. Decreasing the amount of arable land available per person generates food supply insecurity. This trend exists because population growth is outstripping the expansion rate of the area used for crop production [8]. Solutions such as genetic modifications, agrochemicals, mineral fertilizers, and growth conditioners are tested in order to ensure food security [9,10]. However, these solutions, along with improper land management and excessive soil exploitation, often deteriorate soil quality, leading to a decline in agricultural productivity and soil degradation [11]. The negative impact of human activities on soil has been ongoing since the first agricultural revolution, although the anthropic impact on soil goes back as far as 13,000 years ago [4].

Soil degradation is also a significant global problem. Approximately one-third of the world's cropland is affected by at least one form of degradation, including soil/water pollution, soil water/wind erosion, the loss of soil organic matter (SOM), nutrient imbalances, salinization and acidification, crust formation, and the loss of soil biodiversity [11,12]. Whilst soil continues to degrade at a rate of 5–10 billion hectares annually [13], the responsibility for addressing soil conservation and management falls on all of us, regardless of background, knowledge, or profession. Therefore, on a global scale, significant efforts must be invested to create sustainable measures in order to mitigate or neutralize land degradation. Several policies have been launched to combat land degradation by promoting sustainable agriculture and management. From the United Nations "2030 Agenda for Sustainable Development", which seeks a more sustainable future through a land degradation-neutral world where food production is intensified on existing cropping and pasture lands under sustainable land management practices [14], to the European Commission's "A Soil Deal for Europe", which addresses the Sustainable Development Goals and the Green Deal, together with the European Union Soil Strategy [15]. All policy goals directly or indirectly depend on soil function, land use, and management [16,17], highlighting the need to ensure and preserve soil quality.

Preserving soil quality is essential in implementing sustainable agriculture and safeguarding ecosystem services [18]. Among several other strategies, such as the implementation of cover crops, conservation tillage practices, balanced fertilization, and crop rotation [11,19], soil quality can be improved by applying soil amendments [20–22]. Soil amendments refer to materials obtained from different processes that are used to improve soil productivity and quality [23].

There are two categories of soil amendments: (1) organic materials, such as biochar, straw, pomace, manure, sawdust, and compost, and (2) inorganic materials, including sand, gypsum, vermiculite, zeolite, and lignite [24,25]. Soil amendments, both organic and inorganic, improve the physical and biological properties of soil, increase carbon sequestration, restore saline and contaminated soils, and increase crop yields and fertilizer efficiency [26]. Generally, their impact on soil quality is primarily positive, regardless of the climate conditions and soil type [27].

The use of organic amendments has its economic aspect. The high prices of inorganic fertilizers favor organic amendments as a desirable and acceptable alternative for meeting the demand for nutrients in plant production. In addition, they also have a positive influence on soil properties and reduce dependence on inorganic fertilizers [28,29]. How and to what extent organic amendments will affect soil properties depends on several factors: type of material used, the amount used in a certain area, duration of application, climate conditions, soil type, soil management practices, and cropping systems [30,31].

When using organic amendments in plant production, emphasis is placed on increasing the soil organic matter (SOM) content, which is a crucial factor because a lack of SOM can lead to multiple negative changes in the soil. Reduced water storage capacity and porosity, soil compaction, and low infiltration capacity are just a few examples [32], as well as increased runoff and the loss of the topsoil layer [33]. All of the mentioned elements emphasize the importance of proper soil management, including soil conditioning using organic amendments. Future paragraphs will detail the impact of soil conditioning on soil quality. Several studies highlighted the adverse effects of improper organic amendment addition in this context. For instance, research conducted in the USA [34] reported a decrease in soil nitrogen following biochar application, regardless of application rate. Similarly, compost derived from the wine industry has been shown to elevate soil pH, which is particularly harmful for crop production in the naturally alkaline soils of South Africa [35]. Conversely, detrimental trends associated with animal manure applications were observed in Bangladesh [36], exacerbating soil acidification issues. The presented examples warn farmers that the use of particular organic amendments should align with crop needs, soil characteristics, and environmental conditions.

This paper presents a unique approach, discussing the impacts of organic amendments, namely compost, vermicompost, biochar, pomace, and manure, on the physical and chemical properties of soil. Our discussion is based on the most recent and relevant review and meta-analysis articles. In cases where review and meta-analysis papers were unavailable for a given topic, we turned to the most recent and relevant research papers (Tables 1–4). Importantly, no previous review or meta-analysis articles have synthesized or integrated all the organic amendments named above into a single source, nor have they linked such practices to the emerging topic of sustainable agriculture and restoration strategies. Further, no collective papers were found that considered the contrasting effect of these amendments on such a range of (physical and chemical) soil properties with different textures. This paper fills that gap, providing a comprehensive review of the impacts of organic amendments on soil properties.

For this review, we extensively searched all published reviews, meta-analyses, and research articles on the available databases that had been published up until 31 December 2023. Our search terms included “soil amendments”, “organic amendments”, “biochar”, “compost”, “vermicompost”, “manure”, “dung”, and “pomace”, combined with “soil”, “soil organic matter”, “water erosion”, “soil quality”, “land degradation”, “tillage”, “soil management”, and other keywords related to land degradation and soil restoration strategies. We only included articles written in English and those that included replicated treatments and control treatments without the use of organic amendments for comparison purposes. The statistical results reported in the published articles were used to draw statistical conclusions about the amendments’ impacts. Note that a few relevant articles in this review did not provide statistical changes or numerical differences in the improvement of soil properties, only general statements about the impact of the amendments on some qualitative services (i.e., soil quality, structure improvement, soil fertility, etc.). This review focuses on the most relevant amendment-induced changes in soil systems and land degradation reclamation, and discusses how organic amendments affect agricultural production.

**Table 1.** Soil amendment impact on soil physical properties.

| Rn | Texture | Duration | Tillage | Amendment | Base Material | Rate (t ha$^{-1}$) | BD | MWD | TP | WSA | SWC |
|---|---|---|---|---|---|---|---|---|---|---|---|
| [31] | L | ST | Con | Ct | | 0 | - | | | | |
| | | | | Com | Sheep manure | 2 | NE | | | | |
| | | | | | | 4 | D | | | | |
| | | | | | | 6 | D | | | | |
| | | | | | | 8 | NE | | | | |
| | | | | | | 10 | D | | | | |
| | | | | Str | Maize | 6 | D | | | | |
| [35] | SL | ST | ND | Ct | | 0 | | | | | - |
| | | | | Com | Winery solid waste | 5 | | | | | NE |
| | | | | | | 10 | | | | | NE |
| | | | | | | 20 | | | | | NE |
| | | | | | | 40 | | | | | NE |

**Table 1.** *Cont.*

| Rn | Texture | Duration | Tillage | Amendment | Base Material | Rate (t ha$^{-1}$) | BD | MWD | TP | WSA | SWC |
|---|---|---|---|---|---|---|---|---|---|---|---|
| [37] | C | ST | ND | Ct |  | 0 |  | - |  |  |  |
|  |  |  |  | Com | Sheep manure | 4.5 |  | I |  |  |  |
|  |  |  |  |  |  | 9 |  | I |  |  |  |
|  |  |  |  |  |  | 13.5 |  | I |  |  |  |
|  |  |  |  |  |  | 18 |  | I |  |  |  |
|  |  |  |  | Fm | Sheep manure | 4.5 |  | I |  |  |  |
|  |  |  |  |  |  | 9 |  | I |  |  |  |
|  |  |  |  |  |  | 13.5 |  | I |  |  |  |
|  |  |  |  |  |  | 18 |  | I |  |  |  |
| [38] | SiCL | LT | Con | Com | Poultry manure | 8.97 |  | NE |  |  |  |
|  |  |  |  |  |  | 8.97 |  | I |  |  |  |
|  |  |  |  | Bc | Walnut shells | 10 |  | NE |  |  |  |
|  |  |  |  |  |  | 10 |  | NE |  |  |  |
| [39] | S | ND | ND | Dd | Food waste | 20 | NE |  |  | NE |  |
|  |  |  |  | Vcom | Digestate food waste | 20 | NE |  |  | NE |  |
|  |  |  |  | Com | Sewage sludge, green waste | 20 | NE |  |  | I |  |
|  |  |  |  | Vcom | Sewage sludge | 20 | NE |  |  | I |  |
|  |  |  |  | Ct |  |  | - |  |  | - |  |
|  | LC |  |  | Dd | Food waste | 20 | NE |  |  |  |  |
|  |  |  |  | Vcom | Digestate food waste | 20 | NE |  |  | I |  |
|  |  |  |  | Com | Sewage sludge, green waste | 20 | NE |  |  | I |  |
|  |  |  |  | Vcom | Sewage sludge | 20 | NE |  |  | I |  |
|  |  |  |  | Ct |  |  | - |  |  | - |  |
| [40] | SL | LT | ND | Ct |  | 0 |  |  | - | - | - |
|  |  |  |  | FYM | Solid + liquid phase | 15 + 4 |  |  | I | I | I |
| [41] | SiC | LT | Con | Ct |  |  | - |  |  |  | - |
|  |  |  |  | M | Olive leaves | 236 | D |  |  |  | NE |
|  |  |  |  | Pom | Olive mill waste | 270 | D |  |  |  | NE |
| [42] | SiC | LT | Con | Bf |  | 0 | - |  |  | - | - |
|  |  |  |  | Ct |  | 0 | NE |  |  | I | NE |
|  |  |  |  | FYM | Cattle manure | 38 | D |  |  | I | NE |
|  | SiL | LT | Con | Ct |  | 0 | - |  |  | - | - |
|  |  |  |  | FYM | Cattle barn | 20 | NE |  |  | NE | NE |
|  |  |  |  |  |  | 30 | NE |  |  | NE | NE |
|  | SL | LT | Con | Ct |  | 0 | - |  |  | - | - |
|  |  |  |  | FYM | Cattle slurry | 25 | NE |  |  | NE | I |
|  |  |  |  |  |  | 37.5 | D |  |  | NE | I |
| [43] | SiL | LT | ND | Bc | Paper fiber | 10 |  |  |  | I |  |
|  |  |  |  |  |  | 20 |  |  |  | I |  |
| [44] | L | LT | Con | Ct |  | 0 |  |  |  | - |  |
|  |  |  |  | Com | Grape pomace, poultry droppings, mown grass, and straw | 30 |  |  |  | I |  |
|  |  |  |  |  |  | 60 |  |  |  | I |  |

**Table 1.** *Cont.*

| Rn | Texture | Duration | Tillage | Amendment | Base Material | Rate (t ha$^{-1}$) | BD | MWD | TP | WSA | SWC |
|---|---|---|---|---|---|---|---|---|---|---|---|
| [45] | C | LT | Con | Ct | | 0 | - | | - | | |
| | | | | Gm | ND | ND | D | | I | | |
| | | | | FYM | | 35 | D | | I | | |
| [46] | SiC | LT | Con | Ct | | 0 | - | | | | |
| | | | Min | FYM | ND | 15 | D | | | | NE |
| | | | Red | | | 30 | D | | | | NE |
| [47] | SiL | LT | ND | Ct | | 0 | - | - | | | |
| | | | | FYM | ND | 10 | D | I | | | |
| [48] | L | LT | Con | Ct | | 0 | - | | | | |
| | | | | FYM | Cattle manure—composted | 10 | NE | | | | |
| [49] | LS | ST | ND | Ct | | 0 | D | | | | I |
| | SL | | | Bc | Pine wood mill waste | 4 | - | | | | I |
| | | | | | | 20 | D | | | | I |
| | L | | | | | 100 | - | | | | - |
| | | | | | | 100 | - | | | | I |
| | SiL | | | | | 100 | D | | | | - |
| | SiCL | | | | | 100 | D | | | | - |
| | | | | | | 100 | D | | | | I |
| [50] | SiL | ND | Htt | Ct | | 0 | | - | | - | |
| | | | | Bc | Rice straw | 0; 11.25; 22.5 | | NE | | I | NE |
| | | | | | Maize straw | 0; 11.25; 22.5 | | NE | | I | NE |
| | | | | | Wheat straw | 0; 11.25; 22.5 | | NE | | I | I |
| | | | | | Rice husk | 0; 11.25; 22.5 | | NE | | I | I |
| | | | | | Bamboo | 0; 11.25; 22.5 | | NE | | I | I |
| [51] | CL | LT | Conservation | Ct | ND | 0.015 per plant | - | | - | | - |
| | | | | Omw | | 0.8 per plant | NE | | NE | | NE |
| | | | | Com | Olive pomace | 0.06 per plant | NE | | NE | | NE |
| | | | | | | 0.12 per plant | NE | | I | | NE |
| [52] | SiL | ST | Con | Ct | | 0 | - | | | - | |
| | | | | Com | Olive pomace | 4 | NE | | | NE | D |

**Table 1.** *Cont.*

| Rn | Texture | Duration | Tillage | Amendment | Base Material | Rate (t ha$^{-1}$) | BD | MWD | TP | WSA | SWC |
|---|---|---|---|---|---|---|---|---|---|---|---|
| [53] | SL | ST | ND | Ct |  | 0 | - |  | - |  | - |
|  |  |  |  | Bc | Poultry litter waste | 12.39 | D |  | I |  | I |
|  |  |  |  |  |  | 24.78 | D |  | I |  | I |
|  |  |  |  |  |  | 37.17 | D |  | I |  | I |
|  |  |  |  |  |  | 49.56 | D |  | I |  | I |
|  |  |  |  |  |  | 61.95 | D |  | I |  | I |

Abbreviations: Rn—reference number, C—clay, SiC—silty clay, SiCL—silty clay loam, CL—clay loam, SiL—silt loam, L—loam, SL—sandy loam, LS—loamy sand, S—sand, Bc—biochar, Vcom—vermicompost, Dd—dewatered digestate, FYM—farmyard manure, M—mulch, Pom—pomace, Bf—bare fallow, Gm—green manure, Omw—olive mill wastewater, Htt—hand tool tillage, Str—straw, BD—bulk density, MWD—mean weight diameter, TP—total porosity, WSA—water-stable aggregates, SWC—soil water content, ST—short-term, LT—long term, Con—conventional, Red—reduced, Min—minimum, ND—non-defined, NE—no effect, I—increased, D—decreased.

**Table 2.** Soil amendment impact on soil chemical properties.

| Rn | Texture | Duration | Tillage | Amendment | Base Material | Rate (t ha$^{-1}$) | pH | SOM | TN | P | K | C |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| [31] | L | ST | Con | Ct |  | 0 | - | - |  |  |  |  |
|  |  |  |  | Com | Sheep manure | 2 | D | NE |  |  |  |  |
|  |  |  |  |  |  | 4 | D | I |  |  |  |  |
|  |  |  |  |  |  | 6 | D | I |  |  |  |  |
|  |  |  |  |  |  | 8 | NE | I |  |  |  |  |
|  |  |  |  |  |  | 10 | D | I |  |  |  |  |
|  |  |  |  | Str | Maize | 6 | NE | I |  |  |  |  |
| [34] | SiL | ST | Con | Ct |  | 0 | - | - |  | - |  |  |
|  |  |  |  | Bc | Douglas fir | 11.2 | I | I | D | I |  |  |
|  |  |  |  |  |  | 22.4 | I | I | D | I |  |  |
|  |  |  |  |  |  | 44.8 | I | NE | D | I |  |  |
| [35] | SL | ST | ND | Ct |  | 0 | - |  |  |  |  |  |
|  |  |  |  | Com | Winery solid waste | 5 | NE |  |  |  |  |  |
|  |  |  |  |  |  | 10 | I |  |  |  |  |  |
|  |  |  |  |  |  | 20 | I |  |  |  |  |  |
|  |  |  |  |  |  | 40 | I |  |  |  |  |  |
| [36] | ND | ST | ND | Ct |  | 0 | - |  |  |  |  |  |
|  |  |  |  | FYM | Cow dung | 10 | D |  |  |  |  |  |
|  |  |  |  |  | Chicken manure | 10 | D |  |  |  |  |  |
|  |  |  |  |  | Cow dung + chicken manure | 10 | D |  |  |  |  |  |

**Table 2.** *Cont.*

| Rn | Texture | Duration | Tillage | Amendment | Base Material | Rate (t ha$^{-1}$) | pH | SOM | TN | P | K | C |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| [37] | C | ST | ND | Ct |  | 0 | - |  |  |  | - | - |
|  |  |  |  | Com | Sheep manure | 4.5 | NE |  |  |  | NE | NE |
|  |  |  |  |  |  | 9 | NE |  |  |  | NE | NE |
|  |  |  |  |  |  | 13.5 | NE |  |  |  | I | NE |
|  |  |  |  |  |  | 18 | NE |  |  |  | I | NE |
|  |  |  |  | FYM |  | 4.5 | NE |  |  |  | NE | NE |
|  |  |  |  |  |  | 9 | NE |  |  |  | NE | NE |
|  |  |  |  |  |  | 13.5 | NE |  |  |  | I | NE |
|  |  |  |  |  |  | 18 | NE |  |  |  | I | NE |
| [40] | SL | LT | ND | Ct |  | 0 |  | - |  |  |  |  |
|  |  |  |  | FYM | Solid + liquid phase | 15 + 4 |  | I |  |  |  |  |
| [41] | SiC | LT | Con | Ct |  |  | - | - |  |  |  |  |
|  |  |  |  | M | Olive leaves | 236 | NE | I |  |  |  |  |
|  |  |  |  | Pom | Olive mill waste | 270 | NE | I |  |  |  |  |
| [42] | SiC | LT | Con | Bf |  | 0 | - | - | - | - | - |  |
|  |  |  |  | Ct |  | 0 | NE | NE | NE | D | D |  |
|  |  |  |  | FYM | Cattle manure with straw | 38 | NE | I | I | I | I |  |
|  | SiL |  |  | Ct |  | 0 | - | - | - | - | - |  |
|  |  |  |  | FYM | Cattle barn | 20 | NE | NE | NE | NE | NE |  |
|  |  |  |  |  |  | 30 | NE | NE | NE | NE | NE |  |
|  | SL |  |  | Ct |  | 0 | - | - | - | - | - |  |
|  |  |  |  | FYM | Cattle slurry | 25 | NE | I | I | I | I |  |
|  |  |  |  |  |  | 37.5 | NE | I | I | I | I |  |
| [47] | SiL | LT | ND | Ct |  | 0 | - |  | - | - | - |  |
|  |  |  |  | FYM | ND | 10 | I |  | I | I | I |  |
| [48] | L | LT | Con | Ct |  | 0 | - | - | - | - | - |  |
|  |  |  |  | Residues |  |  | NE | I | NE | NE | NE |  |
|  |  |  |  | FYM | Cattle manure—composted | 10 | NE | I | NE | NE | NE |  |
|  |  |  |  |  |  | 60 | NE |  | I | I | I |  |
| [52] | SiL | ST | Con | Ct |  | 0 | - | - |  | - | - |  |
|  |  |  |  | Com | Olive pomace | 4 | NE | NE |  | NE | I |  |
| [53] | SL | ST | ND | Ct |  | 0 | - |  |  | - | - | - |
|  |  |  |  | Bc | Poultry litter waste | 2.02 | I |  |  | I | I | I |
|  |  |  |  |  |  | 4.05 | I |  |  | I | I | I |
|  |  |  |  |  |  | 6.07 | I |  |  | I | I | I |
|  |  |  |  |  |  | 8.1 | I |  |  | I | I | I |
|  |  |  |  |  |  | 10.12 | I |  |  | I | I | I |

**Table 2.** *Cont.*

| Rn | Texture | Duration | Tillage | Amendment | Base Material | Rate (t ha$^{-1}$) | pH | SOM | TN | P | K | C |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| [54] | S | LT | Htt | Ct | | 0 | - | | - | - | - | |
| | | | | FYM | Sheep manure with straw | 20 | D | | NE | NE | NE | |
| | | | | | | 40 | D | | I | I | NE | |
| | | | | | | 60 | D | | I | I | NE | |
| | | | | Com | Sewage sludge | 20 | D | | NE | I | NE | |
| | | | | | | 40 | D | | I | I | NE | |
| | | | | | | 60 | D | | I | I | NE | |
| | | | | | Municipal solid waste | 20 | D | | NE | NE | NE | |
| | | | | | | 40 | NE | | NE | NE | NE | |

Abbreviations: Rn—reference number, C—clay, SiC—silty clay, SiL—silt loam, L—loam, SL—sandy loam, S—sand, Ct—control, Com—compost, Bc—biochar, FYM—farmyard manure, M—mulch, Pom—pomace, Bf—bare fallow, Htt—hand tool tillage, Str—straw, pH, SOM—soil organic matter, TN—total nitrogen, P—phosphorous, K—potassium, C—carbon, ST—short-term, LT—long-term, Con—conventional, ND—non-defined, NE—no effect, I—increased, D—decreased.

**Table 3.** Soil amendment impact on soil chemical properties.

| Rn | Texture | Duration | Tillage | Amendment | Base Material | Rate (t ha$^{-1}$) | Na | Ca | Mg | S |
|---|---|---|---|---|---|---|---|---|---|---|
| [34] | SiL | ST | ND | Ct | | 0 | | | | - |
| | | | | Bc | Douglas fir | 11.2 | | | | I |
| | | | | | | 22.4 | | | | I |
| | | | | | | 44.8 | | | | I |
| [37] | C | ST | ND | Ct | | 0 | | - | - | |
| | | | | Com | Sheep manure | 4.5 | | NE | NE | |
| | | | | | | 9 | | NE | NE | |
| | | | | | | 13.5 | | NE | NE | |
| | | | | | | 18 | | NE | NE | |
| | | | | Fm | Sheep manure | 4.5 | | NE | NE | |
| | | | | | | 9 | | NE | NE | |
| | | | | | | 13.5 | | NE | NE | |
| | | | | | | 18 | | NE | NE | |
| [47] | SiL | LT | ND | Ct | | 0 | | | | - |
| | | | | FYM | ND | 10 | | | | I |
| [52] | SiL | ST | Con | Ct | | 0 | | | | - |
| | | | | Com | Olive pomace | 4 | | | | NE |
| [53] | SL | ST | ND | Ct | | 0 | - | | | |
| | | | | Bc | Poultry litter waste | 2.02 | D | | | |
| | | | | | | 4.05 | D | | | |
| | | | | | | 6.07 | D | | | |
| | | | | | | 8.1 | D | | | |
| | | | | | | 10.12 | D | | | |

**Table 3.** *Cont.*

| Rn | Texture | Duration | Tillage | Amendment | Base Material | Rate (t ha$^{-1}$) | Na | Ca | Mg | S |
|---|---|---|---|---|---|---|---|---|---|---|
| [54] | S | LT | Htt | Ct | | 0 | - | - | - | |
| | | | | FYM | Sheep manure with straw | 20 | NE | NE | NE | |
| | | | | | | 40 | NE | NE | I | |
| | | | | | | 60 | NE | NE | I | |
| | | | | Com | Sewage sludge | 20 | NE | NE | NE | |
| | | | | | | 40 | NE | NE | NE | |
| | | | | | | 60 | NE | I | I | |
| | | | | | Municipal solid waste | 20 | NE | NE | NE | |
| | | | | | | 40 | NE | NE | NE | |
| | | | | | | 60 | NE | NE | I | |

Abbreviations: Rn—reference number, C—clay, SiL—silt loam, SL—sandy loam, S—sand, Ct—control, Com—compost, Fm—fresh manure, Bc—biochar, FYM—farmyard manure, Htt—hand tool tillage, Na—sodium, Ca—calcium, Mg—magnesium, S—sulfur, ST—short-term, LT—long-term, Con—conventional, ND—non-defined, NE—no effect, I—increased, D—decreased.

**Table 4.** Soil amendment impact on soil hydrological response.

| Rn | Texture | Study Duration | Amendment | Base Material | Rate | IR | Runoff | SL |
|---|---|---|---|---|---|---|---|---|
| [52] | SiL | ST | Ct | | 0 | | - | - |
| | | | Com | Olive pomace | 4 | | NE | NE |
| [55] | S | ST | Ct | | 0 | - | - | - |
| | | | Com | Cattle manure | 0.013/1 * | NE | NE | NE |
| | | | FYM | Raw cattle manure | 0.013/1 * | NE | NE | NE |
| | C | | Ct | | 0 | - | - | - |
| | | | Com | Cattle manure | 0.013/1 * | D | NE | NE |
| | | | FYM | Raw cattle manure | 0.013/1 * | D | NE | D |

* Soil was mixed with compost or farmyard manure at 0.013/1 ($w/w$) ratio of dry manure/soil. Abbreviations: Rn—reference number, C—clay, SiL—silt loam, S—sand, Ct—control, Com—compost, FYM—farmyard manure, ST—short-term, IR—infiltration rate, SL—soil loss, NE—no effect, D—decreased.

## 2. Organic Amendments' Impact on Soil Properties

### *2.1. Soil Physical Properties*

Multiple studies have shown the beneficial effects of organic amendments on different soil types, such as clay [37], loam [31], silty clay loam [38], and sandy loam [38,56]. These amendments enhance SOM content, a crucial soil component that functions as a binding agent, fostering aggregate formation [32,57,58]. When applied, soil structure, pore space, and aggregation improvement are detected within a few months [31,39]. While each organic amendment had its unique impact, collectively, they contributed to enriching soil quality, ensuring better plant growth and sustainability across diverse environments.

In recent studies exploring the impacts of various organic amendments on soil quality, diverse findings have emerged, shedding light on their effects across different soils and durations of application. Rivier et al. [39] demonstrated a positive influence within 30 days of adding compost and vermicompost derived from sewage sludge and organic residue to sandy and clay soils. This study emphasized the beneficial impact of these amendments on soil quality within a relatively brief duration. Conversely, Wang et al. [38] highlighted the significant effects on silty clay loam soil after six years of poultry manure compost application at a rate of 9 t ha$^{-1}$ annually. However, insignificant differences were observed within a shorter duration of 2 years, suggesting a time-dependent influence of compost on soil quality, indicating that significant improvements may require extended application periods. Contrasting with the positive effects observed of other organic amendments, Goldberg et al. [55] reported a short-term negative impact of farmyard manure (FYM) application on soil structure and erosion resistance. This adverse effect was noted only 21 days post-application in clay and sandy soils. These findings underscore the diverse and time-dependent nature of organic amendments' impact on soil quality. The effects of organic amendments on soil quality depend on soil type and the time they are applied. Organic amendments generally increase SOM content and promote the formation of aggregates, but their impacts can differ significantly across different soils and time frames. Short-term studies show that amendments like compost and vermicompost have positive effects, while others, such as FYM, may have initial adverse effects. However, long-term studies suggest that significant improvements in soil quality may require extended application periods. Therefore, it is essential to consider the type of organic amendment and its duration of application in sustainable soil management practices.

Evidence of elevated concentrations of SOM after the application of different amendments have been found around the globe, including after the addition of FYM [40], biochar [34], composted olive pomace [59], or non-composted olive pomace [41,60]. Although the variety of amendments and their properties can vary, their impact on SOM elevation is generally positive [61]. Organic amendments contain cations of polyvalent metals ($Ca^{2+}$, $Mg^{2+}$, $Fe^{3+}$), which act in a similar manner to the inorganic binders that promote the formation of macro-aggregates [62]. Such phenomena are documented in improved soil structural characteristics like aggregate size and stability. However, amendments can reveal different effects on different soils. For example, Fu et al. [42] explored the effects of FYM on silty clay, silt loam, and sandy loam soils. The water-stable aggregate (WSA) percentage was significantly higher only in silty clay soil under the high dose of application (38 t $ha^{-1}$) condition. On the opposite side, the long-term application of FYM in a dosage of 15 t $ha^{-1}$ on sandy loam soil creates a residual effect such that even after FYM was stopped, the WSA was at a high level, similar to other treatments with a continuous application of FYM. Therefore, whether FYM will increase or decrease the WSA depends on soil texture and the time of application.

Biochar demonstrated positive effects on WSA levels. Juriga et al. [43] found that applying 10 and 20 t $ha^{-1}$ of biochar to silty loam soil significantly increased the content of the stable macro-aggregates by 9% and 14%, respectively. Simultaneously, it reduced the content of the stable micro-aggregates by 23% and 38%, compared to the total content of water stable micro- and macro-aggregates in the control plots. This trend was associated with an increase in SOMs. Composted materials are another aspect of soil improvement. However, it is necessary to highlight that composts differ depending on the feedstock material and their degree of decomposition, making the final soil results variable. However, composted material applications in sandy and clay soils, in general, positively affect the soil's physical properties [63]. Applying 60 t $ha^{-1}$ of grape pomace compost mixed with mowing residues and straw significantly improves WSA in loamy soils [44]. In clay loam soil, Li et al. [56] observed that pig manure compost and vermicompost significantly increased large macro-aggregates while reducing small macro-aggregates after application at 15 t $ha^{-1}$. In general, soils behaved after applying organic amendments with lower bulk density, whereas aggregate stability, pore volume, and water infiltration were increased. A similar result was noted after applying FYM in works by Mujdeci et al. [45] and Bogunovic et al. [46]. They revealed the positive impact of FYM in reducing soil compaction levels, measured by the bulk density (BD) and penetration resistance (PR) of silty clay [46] after the application of 15 or 30 t $ha^{-1}$ FYM, and of silt loam soil after the application of 10 t $ha^{-1}$ FYM [47]. Moreover, Jensen et al. [40] observed significantly lower BD values after FYM application than control plots in sandy loam soil. Other than FYM, olive pomace has a high organic matter level, reaching 91% [64], which also helps to reduce compaction. Parras-Alcántara et al. [41] reported significant decreases in BD (1.37 to 1.26 g $cm^{-3}$) following

11 years of continuous application of olive pomace at 270 t ha$^{-1}$ to silty clay and silty clay loam soil. Blanchet et al. [48], in a long-term study with FYM application (10 t ha$^{-1}$ y$^{-1}$), found no significant changes for BD compared to other treatments that included mineral fertilizers and crop residue application. Such an absence of differences in BD could result from the tillage system. The diverse findings underscore the nuanced impacts of organic amendments, particularly FYM and olive pomace, on soil BD. These insights highlight the significance of utilizing organic amendments in soil management strategies, recognizing their potential to modify soil physical properties in order to enhance soil quality.

Soil structure predominantly influences the hydrological properties of soil, which regulate physical, chemical, and biological processes within the soil. In this regard, organic amendments are frequently applied in agroecosystems in order to maintain a favorable soil structure, and thus, hydrological and other vital properties [31]. Indeed, it has been shown that organic amendments can significantly affect changes in soil hydrological properties. Dong et al. [31] found that sheep manure compost (2–10 t ha$^{-1}$) can effectively improve the hydrological properties of loam soil. Improvements were closely connected with soil pore system, aggregation size, WSA, and soil differential porosity, leading to a significant increase in soil infiltration.

Organic amendments impact soil water retention capacity and water content. This is especially pronounced in soils enriched by biochar, FYM, and composts [61]. For instance, FYM has shown multiple beneficial effects on the hydrological properties of soil across different environments, soils, and cropping systems. Adding FYM increases the soil water content by increasing water-holding capacity and retention ability [65,66] and water-use efficiency [67,68]. As reported by Jensen et al. [40], FYM had a beneficial effect on plant available water (PAW) in sandy loam-textured soil compared to the control plots. Fu et al. [42] investigated the effects of FYM on silty clay, silty loam, and sandy loam, and found significant PAW improvements in sandy loam soil; while the other soil types showed a positive response as well, the results were not statistically significant. A similar positive effect of FYM on the PAW of sandy loam soil was reported in a study by Blanco-Canqui et al. [65]. The positive effect of manure on PAW was also found in silt loam soil [69] but not in clay soils [70]. Such discrepancies in results indicate that soil type and environment impact FYM efficiency on soil water characteristics. In this context, Ankenbauer and Loheide [71] found that the effect of organic matter on water retention characteristics was more profound on high sand and silt content soil.

Biochar behaves similarly to FYM in terms of impact on soil hydrological properties. Many studies reported a significant rise in soil retention capacity after biochar application [72–74]. This beneficial effect is mainly localized to sandy soils, as documented in a meta-analysis by Rabbi et al. [75], where biochar-enriched soils successfully reduced plant water stress during dry periods [76,77]. Moreover, soils with low silt content are likely to be more hydrologically responsive to biochar application, and changes were more pronounced at higher rates (20 and 100 t ha$^{-1}$) compared to the lower one (4 t ha$^{-1}$) [49]. In current climate crisis, due to climate change, such an effect is desirable in order to survive during pronounced drought periods. However, the success of the biochar application on soil water characteristics, besides soil texture, also depends on biochar particle size, as proved by Lim et al. [78], who found a higher decrease of saturated hydraulic conductivity under larger particle sizes of biochar than under smaller ones, proving that the structure of biochar particles and biochar-soil storage pores contributes to water retention [79]. Biochar also affects water holding capacity (WHC) in two ways. Firstly, the highly porous nature of biochar allows it to retain water, which can increase the overall moisture content. Secondly, biochar improves soil porosity and has hydrophilic functional groups on the surface, enhancing the soil's ability to hold water. However, it is essential to note that the amount of biochar used can limit these effects [80]. Applying 22.5 t ha$^{-1}$ of biochar from various cereals and bamboo to silt loam soil significantly increased WHC by 4.1–11.9% [50]. Conversely, Parras-Alcántara et al. [41] observed a significant decrease in AWC following prolonged application (11 years) of olive pomace at 270 t $ha^{-1}$ on silty clay and silty clay loam-textured soils.

Compost application represents another effective method that improves soil hydrological functions. The positive effect of compost on soil hydrology was recorded for different soil types, including sandy and loamy clay soils [39]. Applying compost by incorporating SOM leads to several changes in the physical and hydrological properties, increasing soil WHC [81]. The effects of compost on soil hydrological functions are more pronounced in coarser-textured soils, whereas the effect is smaller or absent for finer-textured soils [82]. Clay soils have a higher matric potential and smaller pore sizes than sandy soils and, therefore, can hold more water by weight [83]. Although compost can increase WHC due to its high organic matter content, its application does not necessarily affect PAW. Moreover, Kranz et al. [84] reported that when sandy and silt loam soils with medium porosity were amended with high levels of compost, in some cases they would show NE on PAW. Also, they showed that a significant increase in PAW can occur after applying compost to sandy clay loam and high-porosity sandy loam soils. Soil porosity, besides soil texture, also plays a vital role in compost effectivity on soil PAW.

### 2.2. Soil Chemical Properties

Organic amendments modify chemical properties. For example, they can have a positive effect on soil pH through the intake of organic matter, which is usually lowered after frequent fertilization with nitrogen mineral fertilizers [85]. Li et al. [56] noted a rise in soil pH after the application of 15 t $ha^{-1}$ of pig manure compost or vermicompost to clay loam soil. Similar results were found for other soil types [35] and environments, indicating that compost has a liming potential due to its richness in alkaline cations ($K^+$, $Ca^{2+}$, $Mg^{2+}$), which are released with the mineralization of organic matter [83]. Sometimes, compost reduces soil pH [86], which is probably connected to specific conditions during compost production. The use of winery solid waste compost on sandy loam soil, while contributing to increased P and K mineralization, led to a notable rise in soil pH from 7.28 to 8.18 at an application rate of 40 t $ha^{-1}$ [35].

Biochar also exhibits the capability to increase soil pH. This capability stems from its composition of alkaline substances, comprising ash and carbonate ($Ca^{2+}$, $K^+$, and $Mg^{2+}$), its surface properties, and its ability to reduce the exchangeable acid cations ($H^+$ and $Al^{3+}$) [87]. Bista et al. [34] reported a higher pH after biochar application of different dosages (11.2, 22.4, and 44.8 t $ha^{-1}$). However, biochar produced from various sources and at different temperatures showed diverse effects on soil pH [88,89]. Hossain et al. [89] found that the pH reaction of biochar derived from wastewater sludge changes from acidic to alkaline, with an increase in pyrolysis temperature from 300–700 °C. They suggested that it could be used on soils with an alkaline reaction.

In addition to pH, changes in cation exchange capacity (CEC), electrical conductivity, nutrients, and soil organic carbon (SOC) content occur after applying organic amendments. Biochar produced from various sources and at different temperatures showed diverse effects on soil CEC [88,89]. For instance, biochar produced from coffee husk or chicken manure significantly influenced soil CEC more than that produced from eucalyptus sawdust or sugarcane bagasse. Further, they observed that biochar produced at a temperature of 350 °C has a more significant impact on increasing CEC than biochar produced at temperatures of 500 °C and 750 °C [88]. Moreover, biochar application demonstrated positive implications for carbon sequestration, contributing to soil quality and sustainability [90].

The amount of nutrients released during the decomposition of FYM is influenced by various factors: livestock class, age, growth stage, feed and feeding practices, type and amount of bedding materials, and season (climate conditions) [91]. Most nutrients are expected to be released within the initial three years following application. Hence, reapplying the amendment at least every fourth year, with increased application rates, is recommended, while the annual application of smaller quantities is also suggested [92]. The latter is advised as it has been observed that it can significantly enhance crop yields.

Specifically, Oueriemmi et al. [54] noted a more significant effect on barley yield after applying different amounts of FYM in sandy-textured soil during the second year post-application compared to the first year. FYM application (60 t $ha^{-1}$) significantly increased barley yield by 51% (2.26 t $ha^{-1}$) in the first year and 77% (6.96 t $ha^{-1}$) in the second year compared to the control.

As previously mentioned, Fu et al. [42] explored the impact of FYM on various soil types, finding significant increases in SOC and total nitrogen with different application rates on different soil types and crops, and applying 38 t $ha^{-1}$ of FYM on silty clay soil led to a 19% increase in SOC and total nitrogen. On sandy loam soil, there was a significant increase in SOC with application rates of 25 t $ha^{-1}$ and 37.5 t $ha^{-1}$, but this increase was only present in the grass and spring barley plots, and ranged from 27–37%. On plots with maize and winter wheat, the SOC increase was insignificant. On silty loam soil, the level of SOC increased by a maximum of 48%, but this increase was insignificant. This study also found improvements in the nitrogen, phosphorus, potassium, and magnesium concentrations, but these differences were insignificant for each soil type. In sandy loam soil, there was a significant increase in total nitrogen (38–42%), phosphorus (320–840%), potassium (145–225%), and magnesium (50–120%).

Following the application of biochar in quantities of 11.2, 22.4, and 44.8 t $ha^{-1}$, there was a positive impact on the amount and availability of P, K, and S. This was attributed to biochar's ability to supply nutrients to the soil and elevate its pH levels, thereby enhancing their accessibility to plants. However, it should be noted that the nitrogen content in the soil decreased with increasing amounts of biochar, as nitrogen tends to bind to biochar [34].

Olive pomace compost also demonstrated positive effects on the availability of micro- and macro-nutrients, including nitrogen, potassium, zinc, magnesium, and copper, essential for optimal plant growth [93]. However, in order to achieve the effect of enriching the soil with organic carbon qualitatively and quantitatively, the amount of compost that will be applied to the soil should be correctly selected [51]. It was shown that higher amounts do not necessarily produce a proportional increase in SOC. Interestingly, a more favorable effect was achieved with a dose of 60 kg per plant compared to a double dose, particularly on soil with a clay loam texture. Additionally, despite its positive impact on soil and plant growth, applying wet olive pomace at a dosage of 70 t $ha^{-1}$ did not result in significant differences in the crop yield of two wheat cultivars compared to the control without application on sandy loam-textured soil. However, the protein content of wheat grain was positively affected by adding olive pomace, indicating the release of nitrogen in the later stages of plant growth and development [94]. Fernández-Hernández et al. [60], after the application of olive mill waste, found a significant increase in nutrients and a 15% higher olive oil content than those treated with inorganic fertilization. Combining grape pomace with FYM fertilization substantially enhanced maize biomass, and increased soil (SOM, N, P, and K) and plant nutrient content. Additionally, a noteworthy improvement in grape yield was observed, marking a substantial increase of 48% [95].

While organic amendments offer substantial benefits, there are concerns regarding animal-based amendments with a high content of monovalent cations like $Na^+$ and $K^+$, as well as $NH_4^+$ from organic waste nitrogen mineralization. The presence of these components can potentially disturb soil structure by inducing soil colloid dispersion. In order to address this concern, analyzing nutrient concentrations in FYM is imperative. Additionally, accounting for variations across the landscape is crucial for determining and ensuring appropriate application rates, thereby mitigating potential adverse environmental impacts [96]. Different organic amendments exhibit diverse effects on soil properties. FYM, biochar, compost, and pomace display varying impacts based on application rates, soil types, and crops. Understanding these influences is crucial for sustainable soil management and agricultural practices.

## 3. Impact of Organic Amendments on Several Soil Degradation Processes and Restoration Strategies

Soil erosion is the most widespread degradation process occurring naturally but accelerated through human activities, one of which is agriculture [97]. Factors that affect soil erosion in agricultural areas are climatic conditions; soil composition and properties; shape, degree, and length of the slope; soil cover; tillage system; and the overuse of machinery [98–101]. The process occurs through three phases and involves the separation of soil particles in one location and their movement to another under the influence of water or wind energy. The third phase is soil deposition in another location [102,103]. When erosion occurs, it results in the loss of the upper fertile layer, depleting organic matter and nutrients, and affecting soil quality and productivity [104], while decreasing soil water and infiltration capacity [105,106]. When particles are deposited, soil and water can be contaminated with toxic substances, which also seriously impact the environment [107,108].

The pervasive negative effects of soil erosion have spurred global scientific efforts to develop effective mitigation strategies. A range of measures, including crop rotation, cover crops, mulching, conservation tillage, contour cropping, strip cropping, and the application of different amendments, have been investigated [109–112]. However, none of these measures proves universally applicable. Studies indicate that the most favorable outcomes are achieved by measures focused on increasing SOM, complemented by additional measures based on specific conditions [113–116]. In this context, several papers have provided evidence for the beneficial mitigation of erosion using organic amendments, like swine manure [117], olive pomace [41], FYM, and straw [118]. The erosion reductions are mainly attributed to the increase in soil organic matter, vegetation cover, and the protective role of mulch in protecting the soil from disruptive raindrop energy. However, Dugan et al. [52] did not observe a significant reduction in soil losses following the short-term application of olive pomace at a low rate (4 t $ha^{-1}$). These findings underscore the importance of selecting appropriate application rates and considering repeated applications for effective soil conservation. When conditioning to reduce degradation, specific conditions of each organic amendment should be considered. For example, when utilizing biochar for soil erosion control, careful attention should be paid to biochar particle size and the applied dosage. Li et al. [119] revealed that for silt loam-textured soil, smaller applied biochar doses, precisely at 1% and 3%, result in reduced soil losses, while a dose of 7% increases soil and biochar erosion. Concerning particle size, the most effective outcomes were noticed for 1–2 mm particles. Coarse biochar particles demonstrated lower susceptibility to runoff loss than finer particles, proving more effective in preventing soil loss, as noted by Peng et al. [117].

Soil compaction represents a prevalent form of soil degradation that adversely impacts various soil properties. Compaction implies an increase in the volume of the soil mass under an external force, to the detriment of the air-filled pores. Simultaneously, adverse alterations occur in pore volume, size, distribution, connection, and curvature [120–122]. This disturbance leads to a reduction in total porosity and an increase in both BD and PR [123,124]. Furthermore, compaction directly changes soil structure. When it comes to agriculture production, compacted soils have numerous implications. They are more difficult to till and usually have lower plant germination, poor root development, lower plant growth and development, reduced nutrient adsorption, and lower yields [125–127]. Additionally, compacted soils have impaired hydrological properties, resulting in reduced infiltration rates, increased surface runoff, and soil erosion [128–130]. The drivers of soil compaction can be natural or anthropogenic, but more often occur due to heavy machinery, many passes, inappropriate tire pressure, and soil tillage in wet conditions [131–134].

BD and PR are the most commonly used parameters for measuring soil compaction [135]. Previously, it was mentioned that applying FYM and other organic amendments raises SOM content and reduces BD [123,136]. However, BD reduction can be achieved in several ways. Firstly, SOM can stimulate the formation of aggregates, which create larger or smaller pores depending on aggregate size. Secondly, when organic amendments are incorporated, they have a lower density than the soil, which causes a decrease in BD through a dilution effect. Such an effect commonly occurs in (i) short-term studies where an insufficient amount of time has passed for significant changes in aggregate formation and soil porosity, and (ii) long-term studies, when a steady state is reached and there is no significant increment in the formation of macro-aggregates, but significant BD decreases still occur. Similar to FYM, biochar mitigates soil compaction level and decreases soil BD and PR after application. However, for complete and significant changes in coarse-textured soils [137] and fine-textured soils [138,139], very high doses (>40 t $ha^{-1}$) often need to be applied. This is likely due to short periods of time from application to measurement, and the aggregate formation is slow. Biochar's resistance to decomposition makes it challenging to promote aggregate formation and stability in the short term. Similarly, high dosages of biochar reduce BD because of the mixing of materials with different densities. When applying lower doses, biochar more effectively reduces BD in coarse-textured soils than in fine-textured soils, with an average decrease of 14.2% and 9.2%, respectively [140]. Biochar generally increases MWD and aggregate stability, although the absence of positive changes found in some studies may be attributed to site-specific conditions such as climate and clay mineralogy.

Soil sealing and crusting commonly occur during high-intensity precipitation on bare soil or lands with sparse vegetation cover. Raindrops disintegrate soil surface aggregates, clog pores, and reduce soil infiltration. Subsequently, water with dispersed soil particles accumulates on the surface, forming an impermeable layer known as soil crust [141,142]. Thus, sealing and crust formation are closely linked to aggregate stability, soil structure, and the factors promoting them, including increases in SOM, MWD, and the proportion of WSA, which enhance aggregate strength, resistance to external forces, and water movement through the soil [143]. This relationship is evident in previous studies on soil erosion, where the application of organic amendments reduced soil loss and particle detachment due to improvements in soil structure in different textured soils and environments [41,52,62,117,118].

Soil acidity is a prevalent soil degradation process in semi-humid and humid regions [144,145]. Precipitation surplus, the improper application of nitrogen and elemental sulfur fertilizers, and legume cultivation accelerate soil acidification [146–148]. Acid soils have poor soil structure and solubilize iron, aluminium, and manganese, potentially toxic to certain crops [149]. Severe acidification reduces cation exchange capacity and the availability of essential nutrients like phosphorus and molybdenum [150–152]. Soil pH can be mitigated through lime or other acid-neutralizing materials, which can strain farm budgets [153,154].

The impact of FYM on soil acidification varies depending on application conditions. Manure application typically elevates soil pH by introducing base cations and organic matter. As organic matter decomposes, it releases alkalinity through decarboxylation, consuming $H^+$ and raising soil pH [155]. The pH-increasing effect of FYM has been observed across different soil textures, including clay, silt loam, and sandy loam soils [155–158]. However, Roy and Kashem [36] reported a decrease in soil pH following the application of chicken (10 t $ha^{-1}$) and cow manure (10 t $ha^{-1}$) on sandy loam-textured soil exhibiting initial acidity. This pH reduction might be attributed to a weak adsorption capacity, which leads to the leaching of basic cations and the suppression of FYM's positive effect on soil pH. Some soils with high buffering capacities may also resist pH changes [159], and in this case, the addition of organic conditioners should be applied in higher dosages or for prolonged durations. Furthermore, the decomposition of organic matter into humic and fulvic acids could contribute to lowered pH values [160].

Similarly, biochar application can elevate soil pH due to its alkaline nature and oxygenated functional groups [161]. For instance, Da Silva Mendes et al. [53] observed a significant increase in soil pH from 5.35 to 5.85 by applying 10.2 t $ha^{-1}$ of biochar to loamy sand-textured soil. Chintala et al. [162] also noted increases in soil pH with different amounts of biochar application to clay-textured soil, with higher doses leading to greater pH elevations. Other organic amendments, like olive pomace, significantly increase pH in acidic sandy loam [163] and loam [164] soils.

In semi-arid and arid regions, soil salinization and alkalization are prevalent, often due to poor agricultural practices [165–168]. These conditions result in the accumulation of salts in the topsoil, particularly sodium, displacing calcium on the soil's adsorption complex, adversely affecting the soil's physical, chemical, and biological properties. High sodium levels exacerbate soil compaction by clay dispersion [169,170]. Excessive salt concentration in the soil's rhizosphere inhibits plant growth, with some plants experiencing toxicity [171–173]. Salinization and alkalization in agricultural lands are primarily caused by using saltwater for irrigation and inadequate drainage, leading to salt accumulation and waterlogging. Mitigation strategies involve the application of gypsum and sulfur, as well as the using organic amendments, followed by leaching. Organic amendments aim to reduce the sodium adsorption ratio (SAR) and exchangeable sodium percentage (ESP), decrease EC, enhance calcium and magnesium uptake in order to counteract sodium's negative effects, decrease soil pH in order to improve nutrient availability, and increase SOM in order to promote aggregate formation [174]. Researchers used several amendments in their works, such as FYM [175], biochar [176], compost [177], pistachio residue [175], and rice straw [178], which mostly showed a positive impact on soil structure, including a decrease in soil EC and SAR. As well as directly adding organic amendments, several other practices are necessary in order to prevent SOM depletion. Most represented are cover cropping, diverse crop rotation, conservation tillage systems, mulching, crop residue management, balanced fertilization, and the promotion of biodiversity. The utilization of the practices mentioned earlier can enhance SOM, improve soil fertility, and promote sustainable agricultural management practices [178–181]. However, in order to determine the most suitable practice, it is essential to know the site-specific conditions that may affect the success of the reclamation. Figures 1 and 2 show the overall and specific improvements of soil properties in all (Figure 1) soils and across different soil textures (Figure 2).

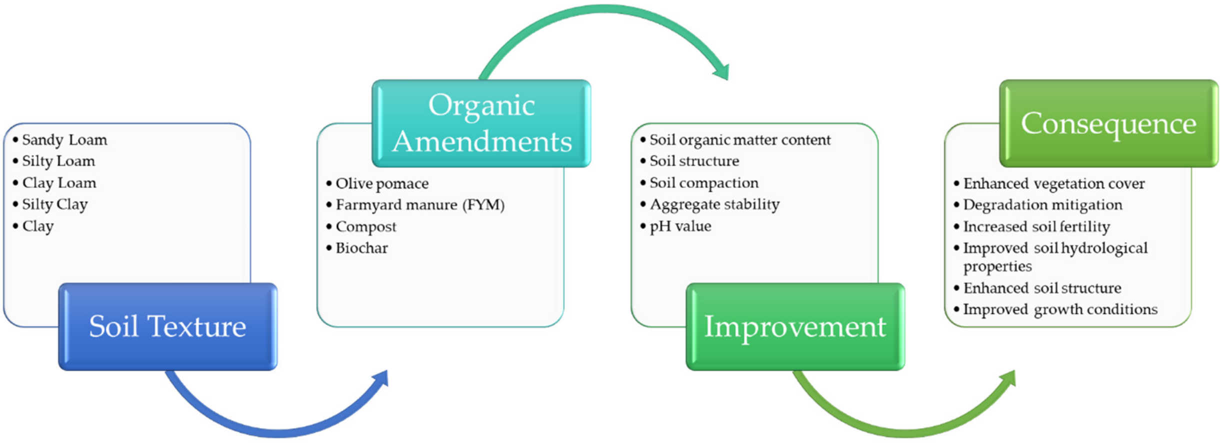

**Figure 1.** Improved soil properties and their environmental and agricultural impact on all soil textures.

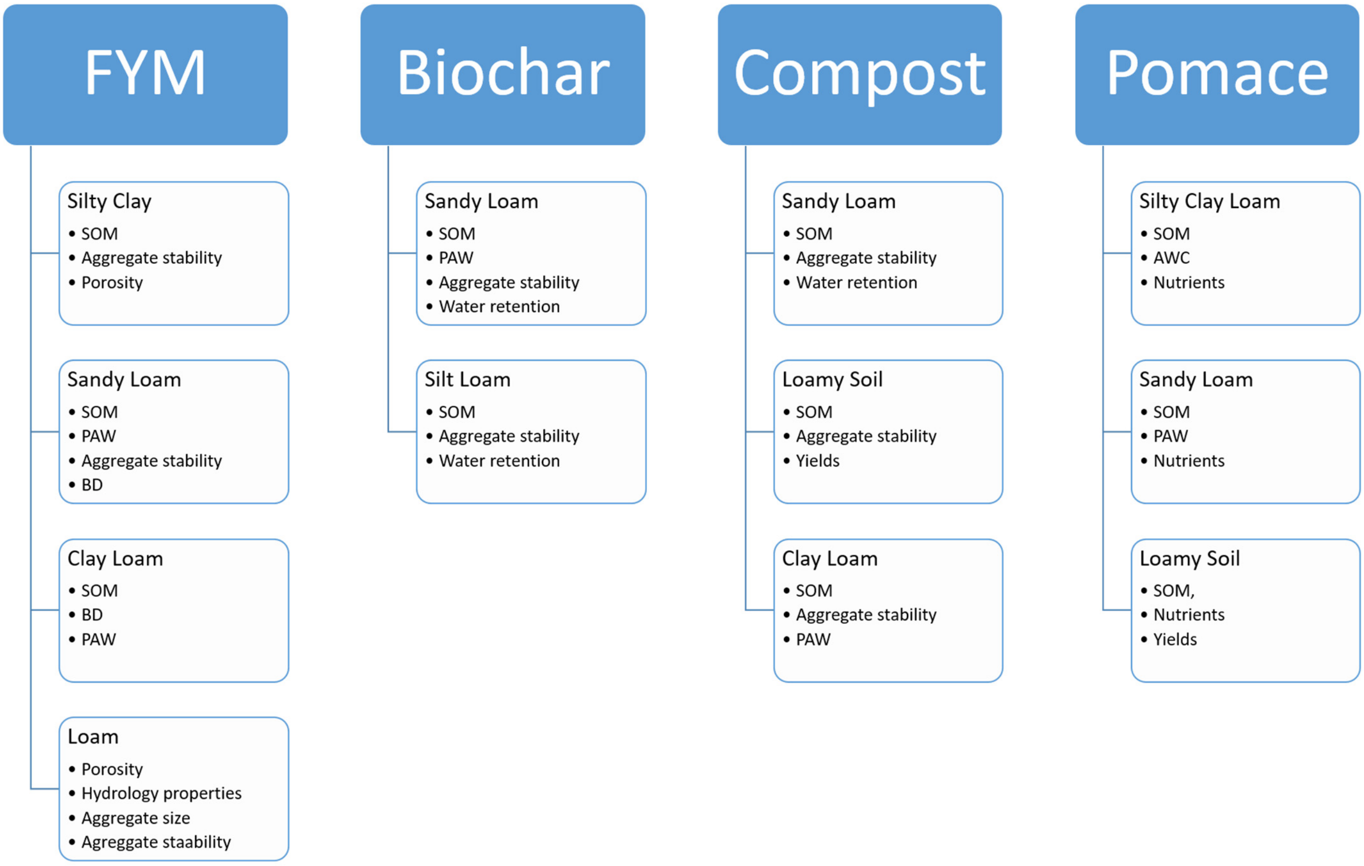

**Figure 2.** Specific soil property improvements in specific soil textures after several organic amendment applications. Abbreviations: SOM—soil organic matter, PAW—plant available water, BD—bulk density.

## 4. Guidance for Further Research

In contemporary agricultural research, the strategic integration of soil amendments with diverse tillage systems emerges as a critical pathway for advancing sustainable crop production. Embracing interdisciplinary advancements in technology, soil science, and agronomy, researchers can delve deeper into unlocking novel opportunities in order to enhance soil quality, increase productivity, and mitigate environmental impacts. The future trajectory of soil amendment management hinges on precision agriculture integration, offering researchers a fertile ground for investigation. Leveraging cutting-edge technologies such as remote sensing, GIS, and GPS enables the precise targeting of soil amendments, necessitating further exploration into optimization algorithms and decision-support systems. Real-time monitoring systems and soil sensors present a rich area for research inquiry, particularly in refining their accuracy, reliability, and compatibility with diverse agroecological contexts.

Additionally, exploring the synergistic blending of different soil amendment types holds promise for elevating soil quality and crop productivity, warranting investigation into optimal blends, application rates, and the long-term effects on soil health and ecosystem services. Advancements in biofertilizer technologies offer a frontier for research, particularly in elucidating the mechanisms underlying microbial interactions, optimizing formulations, and assessing their efficacy under varying environmental conditions. Moreover, the paradigm shifts towards data-driven decision-making necessitate interdisciplinary collaborations in order to develop robust predictive models, innovative data analytic techniques, and user-friendly decision support tools tailored to the needs of diverse stakeholders. Future research endeavors should prioritize longitudinal studies, multi-site trials, and meta-analyses to elucidate the long-term impacts of soil amendments on soil health, crop performance, and ecosystem resilience. By continuously refining methodologies, embracing emerging technologies, and fostering collaborative research networks, scientists can unlock the full potential of soil amendments in order to address the evolving challenges of modern agriculture and pave the way towards a more sustainable food system.

## 5. Conclusions

Organic amendments are indispensable for combating soil degradation processes and restoring soil quality. Most research emphasizes that organic amendments, including pomace, biochar, manure, and compost, offer promising strategies to maintain soil quality and sequester carbon. The effectiveness of these approaches has been duly emphasized. The present study concludes that organic amendments are promising for improving soil structure and carbon sequestration. However, their effectiveness depends on soil texture, climate, and application rates, so tailored approaches are required for optimal results. In several studies, amendment-induced changes were absent, especially for short-term periods, and these may need to be revised in order to contribute to long-term soil resilience to stress and increase soil productivity. This paper further suggests that an approach that integrates different methods is essential for achieving desirable soil quality and maintaining agricultural productivity. It also provides valuable insights and recommendations for policymakers, practitioners, and researchers. Sustainable soil management strategies must effectively combat soil degradation, including comprehensive solutions to combat erosion, compaction, sealing, acidification, and salinization. Organic amendments can improve soil ecosystem services and contribute to climate change adaptation. In the future, more attention should be paid to the interactions between soil management and soil amendments, as well as their effectiveness over time.

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