Organic soil amendments in sustainable and organic agriculture: implications for soil health, carbon sequestration, environmental sustainability and future perspectives

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Abstract. Organic soil amendments have become key components of sustainable and organic agriculture because of their capacity to improve soil fertility while simultaneously enhancing environmental sustainability. Unlike conventional mineral fertilizers, these materials contribute to long-term soil functionality by increasing soil organic matter, stimulating microbial activity, improving nutrient cycling, and strengthening soil structure. This review synthesizes current scientific evidence regarding the classification, mechanisms of action, and agronomic importance of organic soil amendments, with particular emphasis on their effects on soil health, soil organic carbon sequestration, and climate change mitigation. The available literature indicates that amendment effectiveness depends on multiple interacting factors, including amendment type, soil characteristics, climatic conditions, and management practices, highlighting the need for site-specific management strategies rather than universal recommendations. Furthermore, this review critically discusses the environmental benefits associated with nutrient recycling, waste valorization, greenhouse gas mitigation, and ecosystem restoration, while also addressing current limitations related to amendment quality, field performance, and implementation. Overall, organic soil amendments represent fundamental tools for improving agricultural sustainability, supporting climate-resilient farming systems, and promoting integrated soil management approaches capable of simultaneously enhancing productivity, ecosystem functioning, and long-term environmental quality.

Keywords: soil organic carbon, biochar, compost, nutrient cycling, climate change mitigation.

Introduction. Agricultural systems are increasingly challenged to meet the growing global demand for food while reducing their environmental footprint and preserving natural resources. Over the past decades, intensive farming practices have substantially increased agricultural productivity through the extensive use of synthetic fertilizers and other external inputs. However, these practices have also accelerated soil degradation, reduced soil organic matter, disrupted soil microbial communities, increased greenhouse gas emissions, and contributed to nutrient losses, ultimately threatening the long-term sustainability of agricultural production (Bolinder et al., 2020; Badagliacca et al., 2024).

Healthy soils constitute the foundation of sustainable and organic agriculture because they simultaneously support crop productivity, nutrient cycling, water regulation, biodiversity conservation, and climate regulation. Among the numerous indicators of soil quality, soil organic matter (SOM) and soil organic carbon (SOC) are widely recognized as key determinants of soil functionality, influencing physical structure, biological activity, and nutrient availability. Increasing SOM has therefore become a central objective of sustainable soil management, not only to improve agricultural productivity but also to strengthen ecosystem resilience under changing climatic conditions (Tiefenbacher et al., 2021; Maenhout et al., 2024).

Within this context, organic soil amendments have gained considerable attention as multifunctional management tools capable of simultaneously improving soil fertility and environmental sustainability. Materials such as compost, farmyard manure, vermicompost, crop residues, digestates, cover crops, and biochar contribute organic matter and nutrients while stimulating microbial activity, improving soil aggregation, enhancing water retention, and promoting nutrient cycling. Unlike mineral fertilizers, which primarily provide readily available nutrients, organic amendments improve multiple soil functions simultaneously and contribute to the long-term restoration of soil quality (Siedt et al., 2021; Matisic et al., 2024; Badagliacca et al., 2024).

Beyond their agronomic benefits, organic soil amendments are increasingly recognized as valuable tools for climate change mitigation because of their ability to increase soil organic carbon (SOC) stocks while simultaneously improving soil functionality. Gross et al. (2021) demonstrated that biochar consistently enhances SOC accumulation across diverse agricultural systems, whereas Jian et al. (2020) and Bolinder et al. (2020) emphasized the important contribution of cover crops, crop residues, and organic fertilizers through continuous organic matter inputs and biological carbon stabilization. Nevertheless, the effectiveness of carbon sequestration varies considerably with amendment characteristics, soil properties, climatic conditions, and management practices, indicating that no single amendment provides universally optimal results.

Despite the growing body of evidence supporting the benefits of organic amendments, recent reviews emphasize that their environmental performance should be evaluated using an integrated perspective rather than individual indicators alone. Maenhout et al. (2024) argued that carbon sequestration, greenhouse gas emissions, nutrient losses, and soil health should be considered simultaneously when assessing agricultural sustainability. This integrated perspective recognizes that the effectiveness of organic amendments varies substantially among amendment types, environmental conditions, and management practices, reinforcing the need for site-specific management strategies rather than universal recommendations.

Therefore, this review synthesizes current scientific evidence regarding the role of organic soil amendments in sustainable and organic agriculture, with particular emphasis on their influence on soil health, soil organic carbon sequestration, and environmental sustainability. Furthermore, it critically discusses the mechanisms underlying these processes, examines the environmental benefits and potential limitations associated with different amendment strategies, and identifies future research priorities for improving sustainable soil management under increasingly variable climatic conditions.

Literature Review Methodology. This review was conducted through a comprehensive analysis of peer-reviewed scientific literature addressing the role of organic soil amendments in sustainable and organic agriculture, with particular emphasis on soil health, soil organic carbon sequestration, and environmental sustainability. The literature search was performed using major scientific databases, including *Scopus*, *Web of Science*, *ScienceDirect*, *SpringerLink*, *MDPI*, *Google Scholar* and Crossref to identify recent and highly relevant publications.

The search strategy combined keywords such as organic soil amendments, organic fertilizers, compost, farmyard manure, biochar, digestate, cover crops, soil health, soil organic carbon, carbon sequestration, sustainable agriculture, organic agriculture, greenhouse gas emissions, and environmental sustainability. Priority was given to publications released between 2018 and 2025, while earlier studies were considered only when they provided fundamental concepts or widely recognized evidence relevant to the objectives of this review.

Only peer-reviewed journal articles with verified Digital Object Identifiers (DOIs) were included. Preference was given to review papers, meta-analyses, and long-term field experiments because these study designs provide the highest level of evidence for evaluating the long-term effects of organic soil amendments on soil properties and ecosystem functions. Conference proceedings, non-peer-reviewed publications, duplicate studies, and papers lacking sufficient methodological information were excluded from the analysis.

Following the screening process, the selected literature was critically evaluated and synthesized according to four interconnected research themes: (i) the classification and agricultural importance of organic soil amendments, (ii) their effects on soil health, (iii) their contribution to soil organic carbon sequestration and climate change mitigation, and (iv) their environmental benefits, potential trade-offs, and future perspectives. Rather than summarizing individual studies separately, the review integrates findings from complementary investigations to identify areas of consensus, highlight contrasting results, and provide an evidence-based overview of the current state of knowledge. Particular emphasis was placed on recent review articles, meta-analyses, and long-term field experiments because these provide the most robust evidence for evaluating the agronomic and environmental performance of organic soil amendments.

Organic Soil Amendments: Definition, Classification and Mechanisms of Action. According to Siedt et al. (2021), organic soil amendments comprise a diverse group of natural or processed organic materials incorporated into agricultural soils to improve their physical, chemical, and biological properties. Unlike mineral fertilizers, which primarily supply readily available nutrients, these materials enhance long-term soil functionality by increasing soil organic matter, stimulating microbial activity, improving nutrient cycling, and promoting aggregate formation and water retention. As highlighted by Badagliacca et al. (2024), their multifunctional nature allows them to simultaneously improve soil fertility, strengthen ecosystem functioning, and support the transition toward more sustainable agricultural production systems.

The wide diversity of organic amendments reflects their different origins, processing methods, and biochemical characteristics. Commonly used materials include compost, farmyard manure, vermicompost, crop residues, cover crops, digestates derived from anaerobic digestion, and biochar produced through biomass pyrolysis. Although these materials differ substantially in nutrient content, carbon stability, decomposition rate, and microbial interactions, they all aim to restore soil organic matter and improve soil quality. Their selection depends not only on nutrient requirements but also on soil characteristics, climatic conditions, crop systems, and long-term management objectives (Bolinder et al., 2020; Siedt et al., 2021; Badagliacca et al., 2024).

Rather than acting exclusively as nutrient sources, organic amendments influence several interconnected soil processes. The addition of organic substrates stimulates microbial activity responsible for residue decomposition and nutrient mineralization, while simultaneously promoting the formation of stable soil aggregates and increasing soil organic matter. Improvements in soil structure enhance aeration, water infiltration, and moisture retention, creating more favorable conditions for root development and soil biodiversity. These processes operate synergistically, explaining why organic amendments frequently improve multiple indicators of soil health rather than a single soil property (Yang et al., 2025; Xing et al., 2025).

A further distinction among amendment types concerns the stability of the carbon they introduce into the soil. Compost, manure, crop residues, and digestates primarily contribute labile organic carbon that supports microbial activity and nutrient cycling through biological decomposition. In contrast, biochar contains highly stable aromatic carbon structures that decompose much more slowly and therefore contribute more effectively to long-term soil organic carbon sequestration. According to Siedt et al. (2021) and Badagliacca et al. (2024), different organic amendments should be viewed as complementary rather than interchangeable components of sustainable soil management strategies.

Despite the broad consensus regarding the benefits of organic amendments, their agronomic performance is highly context-dependent. Current evidence indicates that amendment effectiveness varies according to soil texture, climatic conditions, amendment composition, application rate, and management history. Furthermore, combining different amendment types or integrating them with complementary practices such as cover cropping, crop rotation, conservation tillage, or optimized nutrient management often produces greater and more persistent improvements than the application of individual amendments alone. These findings support the transition from product-oriented fertilization toward integrated soil management approaches capable of simultaneously enhancing productivity, soil health, and environmental sustainability (Maenhout et al., 2024). The main characteristics of the principal organic soil amendments are summarized in Table 1 (see also Figure 1).

Table 1

Characteristics of the main organic soil amendments

Organic Amendment	*Main source*	*Carbon stability*	*Nutrient availability*	*Primary agronomic functions*	*Potential limitations*
Compost	Aerobically decomposed organic residues	High	Slow and gradual	Increases soil organic matter, improves aggregation, enhances microbial activity and water retention.	Variable nutrient composition; slow nutrient release.
Farmyard manure	Livestock manure mixed with bedding materials	Moderate	Moderate	Improves soil fertility, stimulates microbial biomass, increases soil organic carbon.	Potential N_20 emissions, nutrient losses if poorly managed.
Crop residues	Plant biomass remaining after harvest	Low-Moderate	Slow	Provide continuous carbon inputs, improves aggregate stability, reduces erosion.	Temporary nitrogen immobilization during decomposition.
Cover crops (green manure)	Living plant biomass incorporated into soil	Moderate	Moderate	Enhances soil structure, protects against erosion, increases below-ground carbon inputs.	Management-dependent effectiveness; additional establishment costs.
Digestate	Anaerobic digestion residues	Low	Rapid	Supplies readily available nutrients, promotes nutrient recycling.	Lower contribution to long-term carbon sequestration; possible nutrient leaching.
Biochar	Biomass pyrolysis product	Very high	Very slow	Long-term carbon sequestration, increased cation exchange capacity, improved water retention, microbial habitat.	Higher production costs; effects vary with feedstock and pyrolysis conditions.

Source: Developed by the author based on Bolinder et al. (2020), Siedt et al. (2021), Badagliacca et al. (2024), and Matisic et al. (2024).

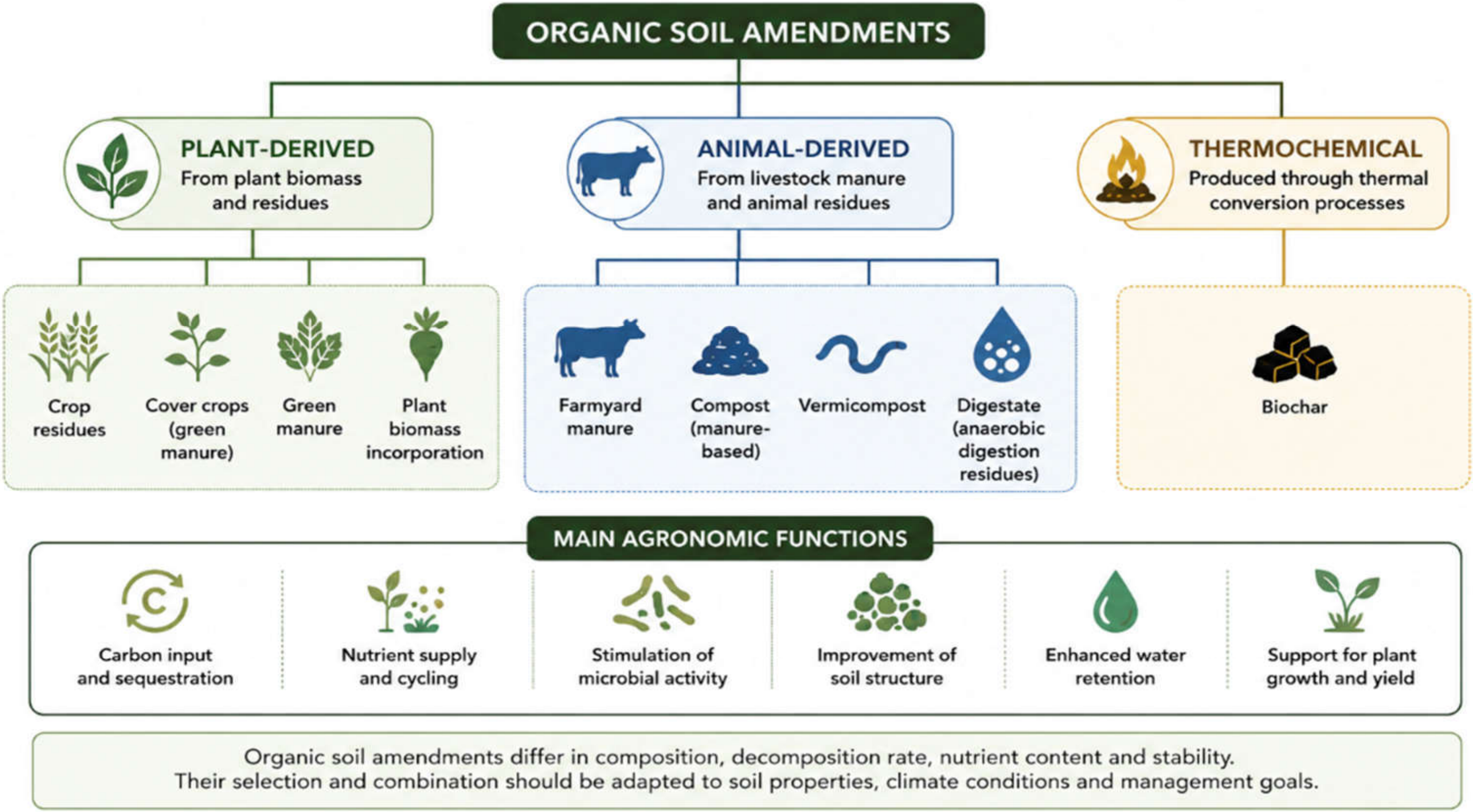

Figure 1. Classification of organic soil amendments according to origin and main agronomic function. Source: developed by the author based on Bolinder et al. (2020), Siedt et al. (2021), Badagliacca et al. (2024), and Matisic et al. (2024).

Effects of Organic Soil Amendments on Soil Health. Soil health represents the capacity of soil to function as a dynamic and living ecosystem capable of sustaining plant productivity, regulating nutrient cycling, maintaining biological diversity, and supporting environmental quality. Because these functions are closely interconnected, improvements in one component of the soil system frequently trigger positive responses in others. Current evidence consistently demonstrates that organic soil amendments enhance soil health through multiple interacting mechanisms rather than isolated physical, chemical, or biological effects (Matisic et al., 2024; Xing et al., 2025).

One of the most widely reported responses to organic amendment application is the gradual increase in soil organic matter, which underpins many improvements in soil functioning. Higher organic matter levels promote aggregate formation, reduce bulk density, increase porosity, and improve water infiltration and retention. These structural modifications create more favorable conditions for root growth while simultaneously reducing soil erosion and improving resilience to drought and intense rainfall events. Long-term field experiments indicate that these benefits become progressively more pronounced with repeated amendment applications, highlighting the cumulative nature of soil restoration processes (Rahman et al., 2022; Siedt et al., 2021).

Recent evidence indicates that soil microorganisms are among the primary drivers of the beneficial effects associated with organic soil amendments. Xing et al. (2025) demonstrated that the incorporation of organic amendments stimulates microbial biomass, enzymatic activity, and functional microbial diversity, thereby accelerating organic matter decomposition and nutrient mineralization. Enhanced microbial activity promotes the cycling of carbon, nitrogen, and phosphorus while contributing to the formation of stable soil aggregates through microbial metabolites and fungal hyphae. Complementary experimental evidence further indicates that these biological responses improve nutrient availability, strengthen soil fertility, and create more favorable conditions for plant growth and long-term soil ecosystem functioning (Yang et al., 2025).

Improvements in soil biological activity are accompanied by more efficient nutrient dynamics. Unlike readily soluble mineral fertilizers, organic amendments release nutrients gradually through microbial decomposition, allowing a closer synchronization between nutrient availability and crop demand. This process increases nutrient use efficiency while reducing nutrient losses through leaching or surface runoff. However, the magnitude of these improvements depends on amendment composition, application rate, soil moisture, and temperature, indicating that nutrient availability remains strongly regulated by environmental conditions rather than amendment application alone (Bolinder et al., 2020; Siedt et al., 2021).

Although the overall evidence strongly supports the positive influence of organic amendments on soil health, important differences exist among amendment types. Compost and farmyard manure generally stimulate microbial processes and nutrient availability more rapidly because they contain relatively labile organic matter. In contrast, biochar exerts slower but often more persistent effects by improving soil structure, increasing water retention, and providing stable habitats for microorganisms. Similarly, cover crops continuously replenish soil organic matter through above- and below-ground biomass inputs, whereas digestates primarily contribute readily available nutrients with comparatively smaller additions of stable carbon. Consequently, no single amendment can be considered universally superior; rather, their effectiveness depends on the specific soil constraints and management objectives being addressed (Gross et al., 2021; Jian et al., 2020; Siedt et al., 2021).

Overall, the available evidence indicates that improvements in soil health result from the interaction of physical, chemical, and biological processes rather than from isolated changes in individual soil properties. This integrated response explains why organic amendments have become fundamental components of sustainable and organic agriculture. At the same time, it emphasizes that successful soil restoration requires management strategies adapted to local soil conditions, climatic variability, and production systems rather than universal amendment recommendations (Maenhout et al., 2024).

Carbon Sequestration and Climate Change Mitigation. Agricultural soils represent one of the largest terrestrial carbon reservoirs and play a central role in global climate change mitigation. Increasing soil organic carbon (SOC) has therefore become a major objective of sustainable soil management because it simultaneously improves soil fertility, strengthens ecosystem resilience, and contributes to reducing atmospheric carbon dioxide concentrations. Unlike short-term nutrient management strategies, practices that enhance SOC provide long-lasting agronomic and environmental benefits by increasing the capacity of soils to store carbon while supporting essential ecosystem functions (Tiefenbacher et al., 2021; Maenhout et al., 2024).

Organic soil amendments contribute to carbon sequestration through two complementary mechanisms. First, they increase carbon inputs by supplying fresh organic substrates that are gradually transformed into stable soil organic matter through microbial decomposition. Second, certain amendments improve the physical protection of organic carbon within soil aggregates and organo-mineral complexes, reducing its susceptibility to microbial degradation. Consequently, SOC accumulation depends not only on the quantity of carbon added but also on the efficiency with which that carbon is stabilized within the soil matrix (Bolinder et al., 2020; Rahman et al., 2022).

The efficiency of carbon sequestration varies substantially among amendment types. Compost, farmyard manure, crop residues, and cover crops primarily increase SOC through continuous organic matter inputs that stimulate microbial activity and humification processes. In contrast, biochar contributes highly stable aromatic carbon that decomposes much more slowly than most natural organic materials, allowing a larger proportion of applied carbon to remain in soil over extended periods. A global meta-analysis by Gross et al. (2021) demonstrated that biochar application significantly increased SOC stocks across a wide range of agricultural systems, with the greatest responses observed in medium- and fine-textured soils and under long-term experimental conditions. Organic fertilizer co-application further enhanced SOC accumulation, emphasizing the importance of integrated management strategies rather than relying on single amendment types.

Cover crops represent another important pathway for increasing SOC because they provide continuous above- and below-ground biomass inputs while reducing soil disturbance between cash crops. Their extensive root systems promote aggregate formation and increase carbon inputs belowground, where carbon is generally more stable than surface residues. Global evidence indicates that cover cropping contributes positively to SOC accumulation, although responses differ according to climate, crop species, soil texture, and management intensity (Jian et al., 2020; Bolinder et al., 2020).

Long-term field experiments consistently demonstrate that repeated applications of organic amendments produce greater SOC gains than short-term interventions. For example, long-term studies combining organic amendments with optimized nitrogen fertilization have reported substantial increases in stable carbon fractions, microbial biomass carbon, aggregate stability, and humus formation, indicating that carbon sequestration is a gradual process requiring sustained management rather than isolated amendment applications (Rahman et al., 2022; Shi et al., 2026).

Despite the overall positive effects, carbon sequestration should not be considered a universal outcome of organic amendment application. Current evidence demonstrates that SOC responses are strongly influenced by pedoclimatic conditions, soil texture, initial carbon stocks, amendment quality, application rate, and management history. Fine-textured soils generally stabilize carbon more efficiently because mineral particles protect organic matter from microbial decomposition, whereas coarse-textured soils often exhibit lower carbon retention. Furthermore, soils approaching carbon saturation tend to show progressively smaller increases in SOC despite continued amendment inputs (Gross et al., 2021; Maenhout et al., 2024).

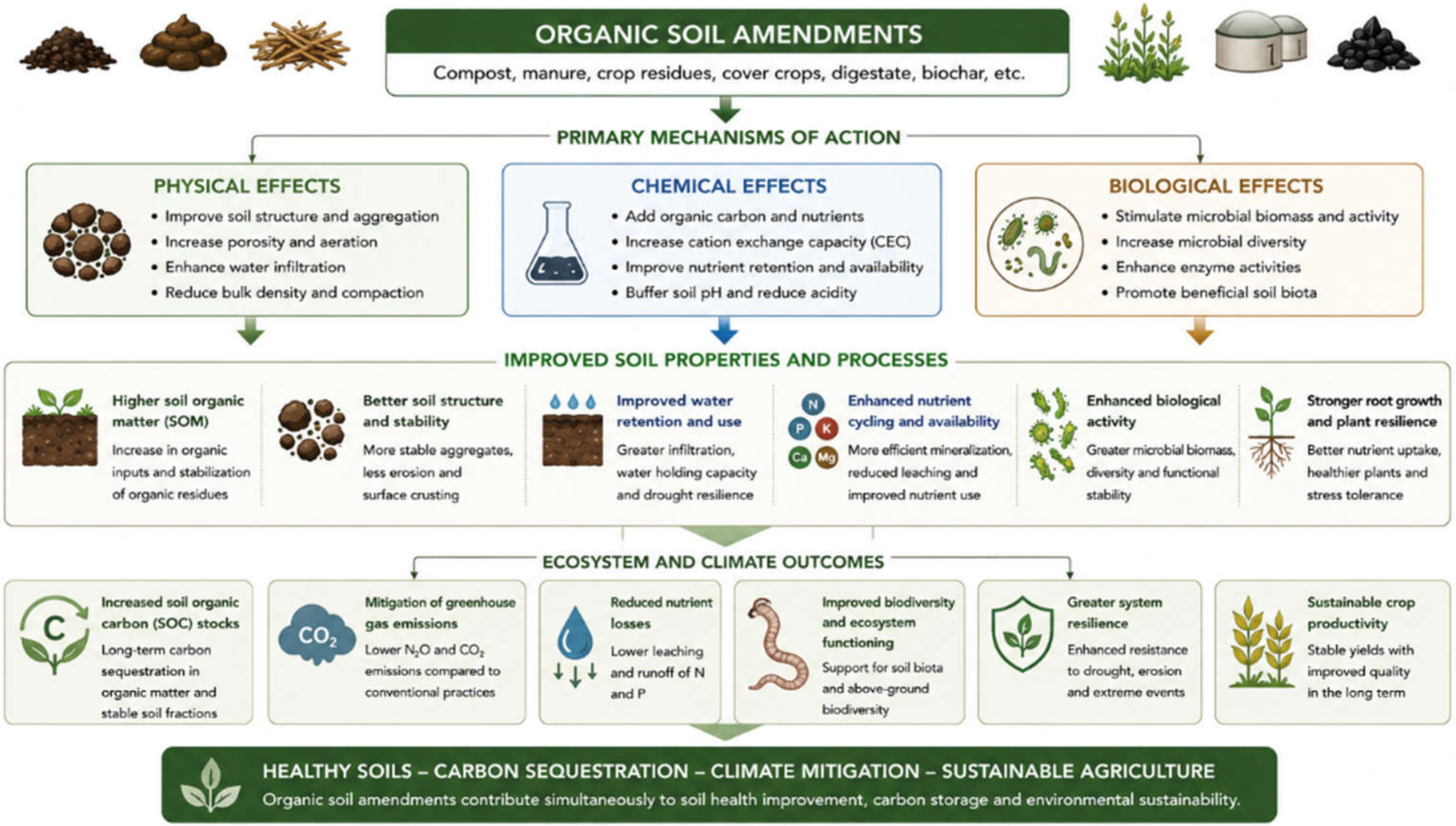

Figure 2. Mechanisms through which organic soil amendments improve soil health, carbon sequestration, and ecosystem functioning. Source: developed by the author based on Bolinder et al. (2020), Jian et al. (2020), Siedt et al. (2021), Gross et al. (2021), Tiefenbacher et al. (2021), Xia et al. (2018), Maenhout et al. (2024), Badagliacca et al. (2024), Matisic et al. (2024), Yang et al. (2025), and Xing et al. (2025).

Rather than representing an isolated environmental objective, carbon sequestration should be evaluated within the broader framework of sustainable soil management. Maenhout et al. (2024) emphasized that assessing soil organic carbon accumulation independently of greenhouse gas emissions, nutrient losses, or ecosystem functioning may lead to incomplete evaluations of agricultural sustainability. Supporting this integrated perspective, Xia et al. (2018) demonstrated that management practices maximizing carbon inputs do not necessarily minimize reactive nitrogen losses, emphasizing the need to balance multiple ecosystem services when designing sustainable soil management strategies. The major mechanisms through which organic soil amendments influence soil health and carbon sequestration are summarized in Figure 2.

Environmental Benefits and Challenges*.* The environmental relevance of organic soil amendments extends far beyond their contribution to crop nutrition and soil fertility. By recycling biodegradable materials and increasing soil organic matter, these amendments support the transition towards more resource-efficient agricultural systems while reducing dependence on synthetic fertilizers. Their incorporation into agricultural soils contributes simultaneously to nutrient recycling, waste valorization, carbon storage, and the restoration of degraded ecosystems, making them central components of circular and climate-smart agriculture (Badagliacca et al., 2024; Matisic et al., 2024).

One of the principal environmental advantages of organic amendments is the recovery of nutrients from agricultural and organic wastes that would otherwise represent disposal challenges. Compost, livestock manure, digestates, and crop residues transform waste streams into valuable agricultural inputs, reducing both waste accumulation and the demand for energy-intensive mineral fertilizer production. Besides improving nutrient availability, these practices promote more circular nutrient flows and increase resource-use efficiency at both farm and regional scales (Badagliacca et al., 2024; Matisic et al., 2024).

Environmental improvements are also associated with enhanced nutrient retention and reduced losses from agricultural soils. Increased soil organic matter improves cation exchange capacity, aggregate stability, and water infiltration, thereby reducing nitrate leaching and phosphorus runoff under appropriate management. Biochar has received particular attention because of its capacity to adsorb nutrients, increase nutrient retention, and reduce nitrate losses in several soil types. Nevertheless, the effectiveness of these processes varies considerably with soil texture, amendment properties, and climatic conditions, indicating that environmental benefits cannot be generalized across all production systems (Borchard et al., 2019; Siedt et al., 2021).

Greenhouse gas mitigation represents another major environmental objective. Increasing soil organic carbon contributes to climate change mitigation; however, the overall greenhouse gas balance depends on simultaneous changes in nitrous oxide (N_2O) and methane (CH_4) emissions. Recent evidence indicates that the effects of organic amendments on N_2O emissions are closely linked to changes in soil microbial processes, nitrogen availability, and amendment composition, emphasizing that greenhouse gas responses depend not only on carbon inputs but also on biological nutrient transformations (Lazcano et al., 2021). Furthermore, recent European syntheses indicate that compost and biochar generally reduce N_2O emissions more consistently than several other amendment types, whereas responses to manure, slurry, digestates, and crop residues are considerably more variable. Moreover, co-application with mineral nitrogen fertilizers may partially offset the environmental benefits achieved through carbon sequestration, emphasizing the need to evaluate complete greenhouse gas budgets rather than SOC accumulation alone (Maenhout et al., 2024; Xia et al., 2018).

Despite these advantages, several practical and environmental challenges remain. The chemical composition of organic amendments varies according to feedstock origin, processing technology, storage conditions, and degree of stabilization, making nutrient availability less predictable than for mineral fertilizers. In addition, some organic materials may contain undesirable contaminants, including heavy metals, residual pharmaceuticals, antibiotics, or pathogens if quality standards are not adequately maintained. Although appropriate treatment substantially reduces these risks, regular quality assessment remains essential before field application (Siedt et al., 2021; Badagliacca et al., 2024). Economic and logistical constraints also influence the adoption of organic amendments. Transportation costs, seasonal availability, storage requirements, and variable product quality may limit their widespread implementation, particularly in intensive agricultural regions located far from organic waste sources. Consequently, successful adoption depends not only on scientific evidence but also on efficient nutrient management planning, supportive agricultural policies, and the development of regional circular economy networks capable of connecting organic waste producers with agricultural users (Badagliacca et al., 2024; Maenhout et al., 2024).

Overall, the current body of evidence indicates that organic soil amendments offer substantial environmental advantages when integrated within well-designed soil management strategies. However, their long-term sustainability depends on balancing carbon sequestration, nutrient recycling, greenhouse gas mitigation, and soil health while minimizing potential environmental risks. This integrated perspective is increasingly recognized as the most appropriate framework for evaluating the environmental performance of sustainable agricultural systems (Maenhout et al., 2024). The principal environmental benefits and potential trade-offs associated with organic soil amendments are summarized in Table 2.

Table 2

Environmental benefits and potential trade-offs associated with organic soil amendments

Environmental aspect	*Major benefits*	*Potential trade-offs / limitations*
Soil organic carbon	Increased SOC storage	Carbon saturation over long periods
Greenhouse gas emissions	Potential reduction of CO_2 emissions	Possible increase in N_2O depending on amendment type
Nutrient cycling	Improved nutrient availability	Risk of nutrient leaching if overapplied
Soil biodiversity	*Enhanced microbial diversity and activity*	Responses vary with soil and climate
Water regulation	Improved water retention and infiltration	Variable effectiveness in coarse-textured soils
Crop productivity	Higher yield stability	Response depends on management practices

Source: Developed by the author based on Xia et al. (2018), Lazcano et al. (2021), Maenhout et al. (2024), Badagliacca et al. (2024), and Matisic et al. (2024).

Future Perspectives. The transition toward sustainable agricultural systems requires a shift from input-oriented management to integrated soil management strategies that simultaneously improve soil health, enhance carbon sequestration, increase nutrient use efficiency, and reduce environmental impacts. Current evidence suggests that future research should focus less on evaluating individual organic amendments in isolation and more on understanding how different management practices interact within complex agroecosystems. This systems-based perspective is expected to become increasingly important as agriculture adapts to climate change and growing resource constraints (Maenhout et al., 2024; Matisic et al., 2024).

One of the major research priorities is the development of site-specific amendment strategies adapted to local soil characteristics, climatic conditions, and cropping systems. The considerable variability observed among studies demonstrates that generalized recommendations cannot consistently maximize agronomic and environmental benefits across different agricultural regions. Future investigations should therefore combine long-term field experiments with precision agriculture technologies to optimize amendment selection, application rates, and nutrient management according to local environmental conditions (Shi et al., 2026; Lu et al., 2025).

Advances in soil microbiome research are also expected to transform the management of organic amendments. Recent studies indicate that microbial diversity and functional microbial communities strongly influence nutrient cycling, soil carbon stabilization, and greenhouse gas emissions. Consequently, integrating microbiome analyses with conventional soil quality indicators may improve the understanding of amendment performance and facilitate the development of management strategies that promote beneficial microbial processes while reducing environmental risks (Xing et al., 2025; Yang et al., 2025).

Another promising direction involves combining multiple sustainable practices rather than relying on single interventions. Increasing evidence suggests that organic amendments produce more consistent long-term benefits when integrated with conservation tillage, cover cropping, diversified crop rotations, and precision nutrient management. These combinations may generate synergistic effects on soil structure, biological activity, carbon sequestration, and crop productivity that exceed the benefits achieved through individual practices alone (Jian et al., 2020; Rahman et al., 2022; Maenhout et al., 2024).

Future research should also adopt more comprehensive assessment frameworks capable of evaluating multiple ecosystem services simultaneously. Rather than focusing exclusively on crop yield or soil organic carbon, future studies should integrate indicators related to greenhouse gas emissions, nutrient losses, biodiversity, water regulation, and economic feasibility. Such multidisciplinary approaches will provide a more realistic evaluation of the environmental performance of organic soil amendments and support the development of evidence-based agricultural policies (Maenhout et al., 2024; Xia et al., 2018).

Finally, strengthening the principles of the circular economy will be essential for expanding the sustainable use of organic amendments. Improved waste valorization technologies, harmonized quality standards, and closer collaboration among researchers, policymakers, farmers, and industry will facilitate the safe recycling of organic residues into agricultural production systems. In parallel, advances in precision agriculture, digital soil monitoring, and life-cycle assessment are expected to improve amendment selection, optimize application strategies, and support more efficient evaluation of their agronomic and environmental performance. Such integrated approaches have the potential to improve soil resilience, reduce dependence on synthetic fertilizers, and contribute to more sustainable and climate-resilient food production systems (Badagliacca et al., 2024; Maenhout et al., 2024; Matisic et al., 2024).

Conclusions. Organic soil amendments have emerged as essential components of sustainable and organic agriculture because of their capacity to improve soil quality while simultaneously addressing several environmental challenges. Unlike conventional nutrient management approaches that primarily focus on maximizing short-term productivity, organic amendments promote long-term improvements in soil functionality by increasing soil organic matter, stimulating biological activity, enhancing nutrient cycling, and improving soil structure. These interconnected processes contribute not only to greater agricultural productivity but also to increased ecosystem resilience under changing environmental conditions.

The evidence synthesized in this review indicates that the effectiveness of organic amendments depends on multiple interacting factors, including amendment type, soil characteristics, climatic conditions, cropping systems, and management practices. Rather than identifying a universally superior amendment, the available literature demonstrates that different organic materials perform complementary functions within agricultural ecosystems. Consequently, selecting appropriate amendment strategies should be based on site-specific management objectives that simultaneously consider soil fertility, carbon storage, nutrient use efficiency, and environmental protection.

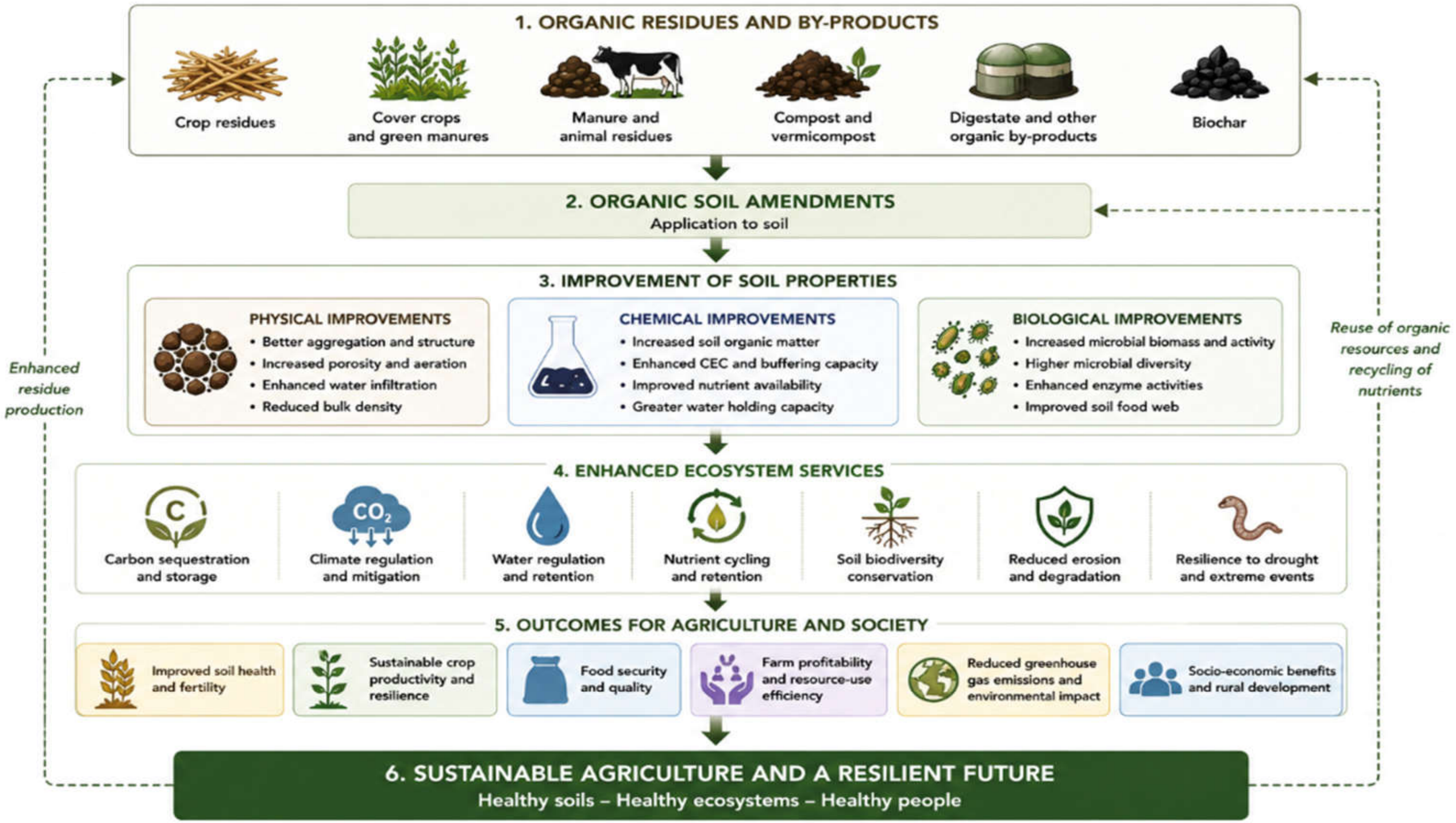

Figure 3. Conceptual framework linking organic soil amendments to sustainable agriculture and ecosystem services. Source: Developed by the author based on Bolinder et al. (2020), Jian et al. (2020), Siedt et al. (2021), Gross et al. (2021), Tiefenbacher et al. (2021), Xia et al. (2018), Lazcano et al. (2021), Maenhout et al. (2024), Badagliacca et al. (2024), Matisic et al. (2024), Yang et al. (2025), Xing et al. (2025), and Shi et al. (2026).

Organic amendments also represent an important opportunity for increasing soil organic carbon stocks and supporting climate change mitigation. However, carbon sequestration should not be considered an isolated management objective. Its long-term benefits are closely linked to improvements in soil health, nutrient retention, microbial functioning, and the overall sustainability of agricultural systems. Likewise, maximizing environmental performance requires balancing carbon accumulation with the reduction of greenhouse gas emissions, nutrient losses, and other potential environmental risks.

Overall, the transition toward sustainable agriculture will increasingly depend on integrated soil management strategies that combine organic amendments with complementary agronomic practices adapted to local environmental conditions. Such approaches offer the greatest potential to improve soil health, strengthen climate resilience, optimize resource use, and support the development of productive agricultural systems capable of meeting future food demands while preserving natural resources. The overall conceptual framework proposed in this review is presented in Figure 3.

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