

Review

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Review

Mitigating Carbon Emissions Through Soil Stewardship: Comparative Insights Across Management Practices

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Abstract

Soils represent a critical leverage point for mitigating global warming, acting simultaneously as major carbon reservoirs and active sources of greenhouse gas emissions under unsustainable management. This review synthesizes current evidence on soil stewardship practices aimed at reducing carbon emissions and enhancing carbon sequestration. Comparative insights are provided across conventional mineral fertilization, organic amendments, and circular fertilization approaches based on agro-industrial by-products. The review integrates findings from field experiments, long-term trials, and life cycle assessment studies to evaluate the effects of different management practices on soil organic carbon dynamics, greenhouse gas fluxes, nutrient use efficiency, and soil biological functioning. Special emphasis is placed on the role of waste-derived fertilizers—such as composts, digestates, vermicompost—in promoting soil carbon stabilization while reducing the environmental burden associated with synthetic inputs. Evidence consistently indicates that soil stewardship strategies grounded in circular economy principles can lower net carbon footprints, improve soil resilience, and mitigate trade-offs between productivity and climate mitigation. By framing soil management within the context of global warming mitigation, this review highlights the multifunctional role of soils as climate regulators and underscores the potential of agro-industrial waste valorization as a scalable pathway toward climate-smart and low-emission agricultural systems.

Keywords: circular economy; greenhouse gas accounting; Life Cycle Assessment (LCA); organic fertilizers; soil organic carbon dynamics

1. Introduction

Soils play a central yet often underestimated role in addressing global environmental challenges [1]. Beyond their primary function in food production, soils regulate key biogeochemical cycles, water dynamics, and ecosystem services that are fundamental for climate change mitigation and environmental sustainability [2]. Agricultural soils, in particular, represent both a major reservoir of terrestrial carbon and a significant source of greenhouse gas (GHG) emissions when managed unsustainably, highlighting their dual role within the climate system [3]. This duality places soils at the core of current debates on climate change, land degradation, and sustainable development.

Globally, soils store more carbon than the atmosphere and terrestrial vegetation combined, making them a critical component of the global carbon cycle [4]. Even relatively small changes in soil organic carbon (SOC) stocks can therefore exert disproportionate effects on atmospheric CO₂ concentrations and climate dynamics.

Land-use change, intensive tillage, and excessive mineral fertiliser application have collectively transformed many soils from net carbon sinks into sources of greenhouse gases (GHGs), releasing carbon dioxide (CO₂), methane (CH₄), and nitrous oxide (N₂O) into the atmosphere[5]. Consequently, soil management has emerged as a critical leverage point for climate-change mitigation, offering both the potential to sequester atmospheric carbon and to reduce agricultural emissions [6]. The Intergovernmental Panel on Climate Change (IPCC) now recognises improved soil management as one of the most cost-effective and immediately deployable pathways to curb global warming[7].

The concept of soil stewardship extends beyond conventional conservation to encompass a holistic strategy for sustaining the biological, chemical, and physical integrity of soils while contributing to climate regulation[8]. Effective stewardship requires integrating agronomic productivity with ecosystem service delivery, specifically, enhancing soil organic carbon (SOC) storage and nutrient-use efficiency while reducing GHG fluxes[8]. Under unsustainable practices, such as heavy mineral fertilisation and residue removal, soils undergo organic-matter depletion, microbial imbalance, and structural degradation. These processes weaken their ability to function as carbon sinks and increase the vulnerability of agro-ecosystems to climatic stress. Conversely, stewardship practices that restore organic inputs, improve aggregation, and foster biological activity can reverse these trajectories, transforming soils into active components of climate-mitigation strategies.

At the same time, managed soils are active sources of greenhouse gases—particularly carbon dioxide (CO₂) and nitrous oxide (N₂O)—whose emissions are strongly influenced by land use and agricultural management practices [9]. Agriculture accounts for a substantial share of anthropogenic GHG emissions, driven largely by fertilization practices, soil organic matter mineralization, and nitrogen transformations [10,11]. As a result, agricultural soils represent a strategic leverage point for climate change mitigation through practices that enhance carbon sequestration while reducing emission intensity.

Over recent decades, the intensification of agricultural systems has profoundly altered soil carbon stocks and nutrient cycling. This intensification has been largely driven by the widespread adoption of synthetic mineral fertilizers and simplified management practices aimed at maximizing short-term productivity [12]. While these approaches have contributed to significant yield gains, they have also been associated with increased GHG emissions, depletion of soil organic matter, and declining ecosystem resilience. Recent study indicate that conventional, input-intensive management systems often overlook the long-term functioning of soils as complex and living systems [13].

In response to these limitations, there is growing recognition that soil management must move beyond yield-oriented paradigms toward more integrated and systemic strategies capable of reconciling agricultural productivity with environmental protection [14]. Within this context, the concept of soil stewardship has emerged as a holistic framework emphasizing the responsible management of soil resources to maintain their capacity to deliver ecosystem services, regulate biogeochemical cycles, and support resilient agroecosystems over time [15]. Soil stewardship recognizes soils as dynamic systems in which physical, chemical, and biological processes are tightly interconnected and responsive to management decisions [16].

The environmental relevance of soil stewardship is increasingly acknowledged within international sustainability frameworks, including the United Nations Sustainable Development Goals (SDGs), particularly those related to climate action (SDG 13), responsible consumption and production (SDG 12), zero hunger (SDG 2), and life on land (SDG 15) [17]. In parallel, climate and environmental policies at global and regional levels are progressively emphasizing the role of soils in mitigation and adaptation strategies, reinforcing the need for management approaches that enhance soil functioning while reducing environmental impacts. Within this broader framework, the valorization of agro-industrial residues through organic fertilization pathways—such as composting, anaerobic digestion, and vermicomposting—has attracted increasing scientific and policy attention. These practices offer the potential to recycle organic wastes, reduce reliance on synthetic fertilizers, and influence soil carbon dynamics. However, their actual contribution to climate change mitigation

depends on complex interactions among processing technologies, soil processes, and management contexts, which remain incompletely understood.

The conceptual framework adopted in this review is summarized in **Figure 1**, which integrates soil carbon and greenhouse gas dynamics, mineral fertilization as a baseline emission hotspot, circular fertilization pathways based on agro-industrial residues, life cycle-based carbon footprint assessment, and emerging policy and carbon market instruments.

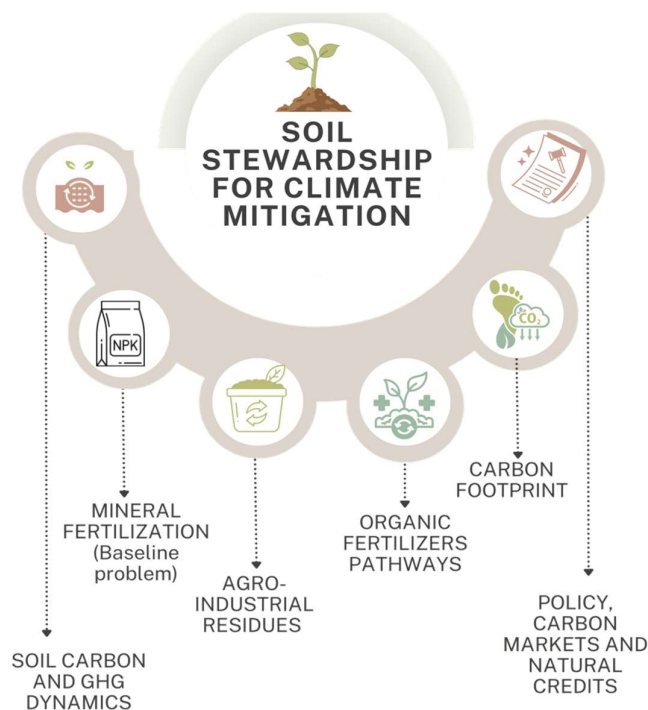


Figure 1. Integrated conceptual framework linking soil stewardship, fertilization strategies, and climate change mitigation.

Against this background, the aim of this review is to critically synthesize recent scientific evidence on soil stewardship strategies for mitigating carbon emissions and enhancing soil carbon sequestration in agricultural systems. The review focuses on fertilization and soil management practices grounded in circular economy principles, with particular attention to the use of agro-industrial residues as alternatives to conventional mineral fertilizers. The analysis is based on peer-reviewed literature published over the last ten years, encompassing 130 scientific articles, including field experiments, long-term trials, and life cycle assessment studies. By integrating agronomic, environmental, and systems-level perspectives, this review aims to identify consistent trends, trade-offs, and knowledge gaps, and to highlight soil stewardship pathways capable of reducing the environmental footprint of agriculture while supporting climate change mitigation and long-term soil sustainability.

2. Soil Carbon Cycling and Greenhouse Gas Emissions in Agricultural Systems

Soil carbon cycling and greenhouse gas (GHG) emissions represent two closely interconnected processes that determine the role of agricultural soils in climate change mitigation and environmental sustainability[4]. As highlighted by recent studies, soil organic carbon (SOC) dynamics are governed by the balance between organic carbon inputs, microbial decomposition, and stabilization

mechanisms, while GHG fluxes reflect the intensity of biogeochemical transformations occurring under different management regimes [3].

Soil organic carbon does not constitute a single homogeneous pool, but rather a continuum of organic compounds characterized by different degrees of bioavailability and turnover. As reported in the literature, SOC can be broadly conceptualized into fractions with contrasting residence times, ranging from rapidly cycling labile pools to more persistent stabilized forms. Labile SOC fractions support microbial activity and nutrient cycling but contribute only transiently to carbon storage, whereas stabilized SOC represents the main component of long-term carbon sequestration in agricultural soils [12].

The stabilization of SOC results from the interaction of physical, chemical, and biological processes. Physical protection within soil aggregates limits microbial access to organic substrates, while chemical associations with mineral surfaces enhance carbon persistence. In parallel, biological transformation of organic inputs by soil microorganisms contributes to the formation of more stable carbon compounds. Recent evidence suggests that the effectiveness of these stabilization pathways strongly depends on soil properties, climate conditions, and long-term management practices [13].

Agricultural management plays a central role in regulating SOC dynamics by controlling both the quantity and quality of organic matter inputs. Long-term observations indicate that systems characterized by limited organic carbon returns to soil are prone to SOC depletion, whereas practices that increase organic inputs can promote SOC accumulation when stabilization mechanisms are preserved [3,12]. However, changes in SOC stocks typically occur slowly and require sustained management over extended time periods.

In parallel with carbon cycling, agricultural soils are recognized as significant sources of greenhouse gas emissions, particularly carbon dioxide (CO₂), nitrous oxide (N₂O), and methane (CH₄). These emissions originate from microbially mediated processes that are highly sensitive to soil conditions and management: CO₂ emissions primarily reflect soil respiration, integrating both microbial decomposition of organic matter and root metabolic activity [9].

Nitrous oxide emissions are of relevance due to their high global warming potential and their strong association with nitrogen availability in soils. As consistently reported in the literature, N₂O emissions are mainly driven by nitrification and denitrification processes, which are stimulated by mineral nitrogen inputs, elevated soil moisture, and fluctuating redox conditions [11]. Consequently, nitrogen management is identified as a key determinant of emission intensity across agricultural systems.

Methane emissions from agricultural soils are generally limited under well-aerated conditions but can become significant in anaerobic environments, such as flooded systems or soils receiving high organic inputs. Changes in water management and residue handling have therefore been shown to alter the role of soils as methane sources or sinks [10].

Importantly, recent studies emphasize the close coupling between SOC dynamics and greenhouse gas emissions. Increased carbon inputs may stimulate microbial activity and short-term emission pulses if not effectively stabilized, whereas management strategies that enhance carbon retention in stable pools can contribute to reduced net greenhouse gas fluxes over longer time horizons [3]. This evidence provides the conceptual basis for evaluating fertilization and soil management strategies discussed in subsequent sections, particularly with respect to their potential to mitigate emissions while maintaining soil functionality.

3. Soil Management Practices and Carbon Dynamics

Agricultural management practices exert a decisive influence on soil carbon dynamics and greenhouse gas (GHG) emissions by regulating both organic matter inputs and the intensity of biogeochemical processes occurring within the soil matrix [18]. While fertilization represents a major driver of soil-atmosphere exchanges, it operates within broader management systems that include tillage regimes, crop rotations, residue handling, and biomass return strategies [19–21]. These

practices interact synergistically, shaping the balance between carbon sequestration and carbon loss in agricultural landscapes[22].

3.1. Tillage Intensity and Soil Carbon Stabilization

Tillage practices strongly influence soil organic carbon (SOC) stocks by altering soil structure, aggregate stability, and microbial accessibility to organic substrates[23]. Conventional intensive tillage disrupts soil aggregates, increases oxygen availability, and accelerates microbial mineralization of organic matter, often leading to SOC depletion over[24]. Different studies indicate that repeated soil disturbance promotes short-term carbon turnover at the expense of long-term carbon stabilization, particularly in systems with limited organic residue return [25,26].

Conversely, reduced tillage and no-tillage systems are generally associated with improved aggregate protection and enhanced physical stabilization of SOC in surface horizons[27,28]. By minimizing soil disturbance, these practices can reduce mineralization rates and promote carbon accumulation in topsoil layers. However, the literature highlights important trade-offs: SOC gains under reduced tillage are often depth-stratified, and potential increases in soil moisture under no-till conditions may stimulate nitrous oxide (N₂O) emissions in certain climatic contexts[29].

Empirical evidence supports this mechanism. For example, Zheng et al. 2022 observed markedly higher SOC under reduced tillage with residue incorporation (+137%) and no-tillage with residue mulching (+131%) compared with conventional tillage combined with residue removal [30]. Similarly, Singh et al. 2022 [27] reported annual SOC increases of 1.22 and 1.0 Mg C ha⁻¹ yr⁻¹ under No-tillage and Reduced tillage with residue incorporation, respectively, while switching from Conventional Tillage to tillage +Residue Incorporation reduced GHG emissions by 16% and the carbon footprint by 78%.

A study of Shi et al. [31] found a 34% increase in SOC stocks under no-tillage combined with residue incorporation and straw return relative to initial soil conditions. Comparable stratified SOC accumulation in surface layers under no-tillage was reported in Ohio (USA), where Deiss et al. [32] measured SOM increases ranging from 0.9% to 22% at 0–20 cm under no-tillage with diversified rotations compared with conventional tillage. In Canada, Liu et al. [33] documented a 9% SOC increase after eight years of NT management.

However, responses are not universally positive. A study conducted in Brazil by Oliveira et al. [34], observed SOC declines after four years of No-Tillage under both chemical fertilizer (–28%) and manure (–22%) relative to the initial soil, although swine slurry application partially restored SOC and increased humic and fulvic acid fractions. Likewise, Poland, Chowaniak et al. [35], reported SOC and TOC reductions under no-tillage relative to conventional tillage, emphasizing the role of site-specific soil cover and erosion processes.

Therefore, the mitigation potential of conservation tillage depends on soil type, climate, and overall system design rather than on tillage reduction alone[36].

3.2. Crop Rotations, Cover Crops, and Residue Management

Crop diversification and residue management are central determinants of carbon inputs to soil[37]. Diverse crop rotations enhance belowground biomass production and root-derived carbon inputs, which are increasingly recognized as critical contributors to persistent SOC formation[38]. Empirical evidence from long-term experiments supports this mechanism. For instance, Zhou et al., [39] reported a 21% increase in SOC under winter crop rotation (including potato, milk vetch, and rape) compared with winter fallow in hydromorphic paddy soils of Jiangxi, China, alongside enhanced crop productivity. Similarly, Zuber et al. [40] observed SOC and soil N increases of 7% and 9%, respectively, under diversified maize–sorghum–wheat rotations compared with conventional systems. In Germany, Grunwald et al. [41] demonstrated that diversified rotations combined with Brassica residue incorporation increased SOC stocks in the 0–10 cm layer, with responses strongly dependent on residue quality and application rate. Cover crops, in particular, provide additional organic inputs during fallow periods, reduce soil erosion, and improve nitrogen retention, thereby

influencing both carbon sequestration and nitrogen cycling dynamics[42]. A study of Haruna and Nkongolo [43] reported an 8% increase in SOM under cover crops compared with bare soil, while in hydromorphic soils winter cover cropping enhanced both SOC accumulation and system productivity [39]. However, responses are not universal: Jagadamma et al. [44] found no significant SOC changes attributable to cover crops in Tennessee, despite higher SOC under no-tillage relative to conventional tillage. Moreover, Radicetti et al. [45] highlighted that cover crop species differ in decomposition dynamics, with hairy vetch generating higher CO₂-C emissions than oat or oilseed rape, reflecting differences in biochemical composition and C:N ratio. Residue management decisions further shape SOC trajectories. Retention of crop residues increases organic matter inputs and supports aggregate formation, whereas residue removal—often practiced for bioenergy or livestock feed—can exacerbate SOC decline if not compensated by alternative organic amendments [46].

Field evidence confirms that residue incorporation significantly enhances SOC compared with residue removal. For example, Gura and Mnkeni [47] observed SOC increases from 1.11% to 1.44% after three years of crop rotation with residue incorporation relative to residue removal. Likewise, Sousa Junior et al. [48], documented annual carbon storage of 0.36 Mg C ha⁻¹ under 100% straw incorporation in Brazilian Oxisols, with cumulative gains increasing over time. Another study shows that , systems combining reduced tillage with residue incorporation achieved SOC increases exceeding 130% compared with conventional tillage and residue removal underscoring the synergistic effect between residue retention and soil disturbance reduction[30].

Long-term experiments consistently demonstrate that systems combining residue retention with diversified rotations tend to exhibit more stable SOC stocks and improved soil structural properties compared with monoculture systems relying on high external inputs [49]. Legume-inclusive rotations further enhance microbial activity and labile carbon fractions: Borase et al. [50], reported increases in SOC, microbial biomass carbon (MBC), and microbial biomass nitrogen (MBN) under legume-based rotations compared with non-legume systems, while another study conducted by Hobley et al. [51], documented progressive C accumulation (4.1% every four years) in clover-based systems receiving balanced PK fertilization.

Importantly, the quality of organic inputs—characterized by carbon-to-nitrogen ratio, lignin content, and biochemical composition—affects decomposition rates and stabilization pathways. Studies comparing organic amendments indicate that more recalcitrant inputs such as biochar preferentially enhance stable C fractions, whereas more labile materials (e.g., vermicompost or legume residues) stimulate microbial activity and short-term mineralization [52]. Furthermore, a recent study demonstrated that in low-clay soils with limited mineral reactivity, grain legume rotations did not significantly increase SOC, highlighting the importance of soil texture and mineral-associated stabilization capacity [53]. Thus, management strategies that diversify both the quantity and quality of biomass inputs tend to enhance the resilience of SOC pools and buffer interannual climatic variability[54].

3.3. Integrated System Management and Carbon–Nitrogen Coupling

Increasingly, the literature emphasizes that soil carbon dynamics cannot be understood in isolation from nitrogen management and broader system interactions [55]. Carbon and nitrogen cycles are tightly coupled through microbial processes, meaning that strategies aimed at increasing SOC must also consider nitrogen availability, mineralization rates, and emission pathways [56]. Excessive nitrogen inputs may stimulate microbial activity and accelerate SOC turnover, whereas insufficient nitrogen supply can limit biomass production and carbon inputs [57, 58]

Field evidence supports this conceptual framework. For example, Pittarello et al. [58] reported SOC increases of 38–53% under organic systems combined with crop rotation compared with conventional tillage, highlighting the synergistic effect of organic nutrient sources and diversified cropping. Similarly, another study observed higher soil C stocks (83–100 Mg C ha⁻¹) under cattle slurry relative to pig slurry, mineral fertilization, or control treatments, indicating that both nutrient form and organic matter quality regulate long-term carbon stabilization[59].

Integrated management approaches seek to optimize this balance by synchronizing nutrient supply with crop demand, enhancing nutrient recycling, and minimizing surplus nitrogen that would otherwise contribute to N₂O emissions or leaching losses [60]. Empirical data confirm that system-level combinations outperform isolated practices. For instance, Singh et al. [27], showed that transitioning from conventional tillage with residue removal to no-tillage with residue incorporation reduced GHG emissions by 16% and carbon footprint by 78%, while increasing SOC stocks. Similarly, another study reported substantial reductions in carbon footprint under crop rotation combined with no-tillage (-79%) and optimized tillage (-46%) compared with conventional tillage [61]. Systems combining reduced tillage, diversified rotations, residue retention, and balanced fertilization are increasingly identified as more effective in sustaining SOC stocks while moderating GHG emissions compared with single-practice interventions [62].

The comparative effects of the main soil management practices discussed above on SOC dynamics and greenhouse gas emissions are summarized in Table 1.

This systemic perspective is particularly relevant when evaluating fertilization strategies discussed in subsequent sections. Organic amendments and circular fertilization pathways should therefore be interpreted not as isolated inputs, but as components of integrated management systems that influence carbon stabilization mechanisms, microbial functioning, and emission intensity. Understanding these interactions provides the conceptual foundation for assessing how fertilization choices interact with broader management practices to shape the climate mitigation potential of agricultural soils.

Table 1. Effects of soil management practices on SOC stocks and GHG emissions across different agroecosystems.

Management practice	Effect on SOC	Effect on GHG / CFP	Underlying mechanisms	Reference
Conventional tillage (CT)	↓ SOC	↑ CO ₂ emissions	Aggregate disruption; enhanced soil aeration; accelerated mineralization of organic matter; reduced residue retention when combined with residue removal	[24,25,35]
Reduced / No-tillage (RT/NT)	↑ SOC (0.9–137%, depth-stratified)	↓ CFP (up to -79%), possible ↑ N ₂ O in humid soils	Reduced soil disturbance; stratification of SOC near surface layers; improved aggregate stability	[27,30,33]
Crop rotation (diversified)	↑ SOC (7–21%)	↓ CFP when combined with NT	Increased root biomass inputs; diversification of residue quality; improved belowground carbon allocation; enhanced microbial activity	[39,40]
Legume-based rotation	↑ SOC, ↑ MBC, ↑ MBN	Improved C–N balance	Biological nitrogen fixation; improved C–N balance; increased microbial biomass (MBC, MBN); interaction with soil clay and mineral reactivity	[50,51]
Cover crops	↑ SOM (up to 8%), variable SOC response	Variable CO ₂ emissions (species-dependent)	Additional biomass inputs; surface residue protection; root-derived carbon inputs; species-dependent decomposition rates	[43,45]
Residue incorporation	↑ SOC (0.36 Mg C ha ⁻¹ yr ⁻¹ ; >130% vs removal)	↓ CFP when combined with NT	Increased carbon input from straw; improved soil aggregation; enhanced C stabilization	[30,48]

Residue removal	↓ SOC	↑ emission intensity	Reduced carbon input to soil; decreased substrate availability for microbial biomass; lower aggregate formation	[46,47]
Organic amendments (manure, slurry)	↑ SOC (up to 83–100 Mg C ha ⁻¹ total stock)	Depends on application rate	Increased humic and fulvic fractions; stimulation of microbial biomass; nutrient-mediated SOC stabilization	[34,58,59]
Biochar	↑ Stable C fractions (32–84%)	Long-term stabilization	Addition of recalcitrant carbon fractions; increased particulate and oxidizable carbon pools; improved microbial habitat; enhanced long-term carbon stabilization	[52]
Integrated systems (NT + CR + residues + balanced N)	↑ SOC increase	Strongest reduction in CFP (–46–79%)	Diversified carbon inputs, optimized nitrogen management; improved nutrient synchronization; enhanced SOC stabilization	[27,61]

SOC (Soil Organic Carbon), GHG (Greenhouse Gases), CFP (Carbon Footprint), CT (Conventional Tillage), RT (Reduced Tillage), NT (No-Tillage), CR (Crop Rotation), RI (Residue Incorporation), RR (Residue Removal), MBC (Microbial Biomass Carbon), MBN (Microbial Biomass Nitrogen), PK (Phosphorus–Potassium fertilization), CO₂ (Carbon dioxide), N₂O (Nitrous oxide).

4. Environmental Impacts of Conventional Mineral Fertilization

Conventional mineral fertilization has played a central role in increasing agricultural productivity over past decades. A study by Bhatt et al. [63] shows that the global use of synthetic nitrogen (N) fertilizers is increasing linearly, with approximately 120 million tons of fertilizer N applied worldwide each year. However, substantial differences exist between developed and developing countries, both in terms of total N consumption and N application rates per hectare of cropland. For instance, global fertilizer N use increased from 51.8 kg ha⁻¹ in 2001 to 65.1 kg ha⁻¹ in 2021, corresponding to an overall increase of 13.7% [63].

Despite their agronomic effectiveness, a growing body of literature highlights the contribution of mineral fertilizers to multiple environmental pressures affecting soil systems. Recent studies emphasize that, while mineral fertilizers efficiently supply nutrients to crops, their long-term implications for soil functioning and environmental sustainability are increasingly questioned [12,13]. In particular, the excessive use of nitrogenous fertilizers can lead to significant environmental pollution, with nearly half of the applied N being lost to the environment, thereby adversely affecting surrounding ecosystems [12,64].

At the global scale, agriculture alone is responsible for approximately 60% of total anthropogenic N₂O emissions, a potent greenhouse gas with a high global warming potential. These emissions substantially contribute to climate change and exert cascading negative effects on agricultural production systems, soil quality, and environmental sustainability.

4.1. Effects of Mineral Fertilization on Soil Organic Carbon and Soil Quality

Several long-term studies indicate that agricultural systems relying predominantly on mineral fertilization tend to provide limited organic carbon inputs to soils, which can compromise the maintenance of soil organic carbon (SOC) stocks over time. As reported by Karstens K., et al. [12], mineral fertilizers alone are often insufficient to offset organic matter losses associated with intensive cropping systems, particularly when combined with residue removal or frequent soil disturbance.

Another study [65] shows that higher use of N fertilizers led to the loss of soil organic matter through mineralization and degrades soil health.

Recent evidence suggests that prolonged mineral fertilization may accelerate SOC mineralization by stimulating microbial activity in the absence of concurrent organic carbon inputs,

leading to stable or declining SOC trends. These effects are frequently accompanied by reductions in aggregate stability and soil structural quality, which negatively affect water retention and increase susceptibility to erosion [14].

Beyond SOC dynamics, several studies report broader declines in soil quality indicators under long-term mineral fertilization. Reduced microbial biomass, lower enzymatic activity, and simplified soil food webs have been observed in comparison with systems receiving organic inputs, reflecting limited substrate availability and altered nutrient stoichiometry[13]. Such changes can impair soil resilience and its capacity to buffer climatic and management-induced stresses.

Overall, the literature converges on the view that mineral fertilization, when applied as a stand-alone strategy, may sustain short-term yields but does not adequately support the long-term maintenance of soil quality and soil organic matter pools.

4.2. Carbon and Nitrogen Losses to the Environment

As consistently documented in the literature, conventional mineral fertilization is associated with substantial carbon and nitrogen losses to the environment, primarily through greenhouse gas emissions and nutrient leaching. Among these pathways, nitrous oxide (N₂O) emissions from fertilized soils represent one of the most critical environmental concerns, due to their strong link with nitrogen inputs and their high global warming potential.

Synthetic nitrogen fertilizers are widely recognized as a major driver of soil N₂O emissions, as they increase the availability of mineral nitrogen substrates that fuel nitrification and denitrification processes. Several studies have shown that crop nitrogen uptake relies not only on fertilizer inputs but also heavily on indigenous soil nitrogen pools. For instance, between 20% and 80% of crop nitrogen uptake originates from soil-derived N, depending on cropping system and soil conditions [66]. Even when fertilizers supply the remaining nitrogen demand, annual nitrogen losses occur whenever N inputs exceed the amount removed by crops at harvest [67].

Insights from studies using ¹⁵N-labelled fertilizers have been particularly valuable in quantifying the fate of applied nitrogen. Radiolabeled nitrogen tracers allow the partitioning of fertilizer-derived N between crop uptake, soil pools, and environmental losses [68]. Using this approach, another study reported that only 44% of applied fertilizer N was recovered in the stems, leaves, and grains of major cereal crops, highlighting the importance of crop residue management to retain nitrogen within the soil-plant system[69]. Across different cropping systems, the average recovery of ¹⁵N-labelled fertilizer nitrogen has been reported to range from 0.4% to 3.3%, indicating that a large fraction of applied nitrogen does not directly contribute to crop nutrition [70,71].

Long-term experiments further confirm these patterns: Dourado-Neto et al. [72] showed that fertilizer-derived nitrogen contributed on average 21.1% of total crop nitrogen uptake (147.0 ± 6.0 kg N ha⁻¹), while the remaining fraction originated from soil nitrogen reserves (Table S1). Similarly, Sebilo et al. [73] demonstrated that, following a single application of ¹⁵N-labelled fertilizer (120 kg N ha⁻¹ for wheat and 150 kg N ha⁻¹ for sugar beet), only 63% of fertilizer N was recovered over a 30-year period, with a substantial proportion rapidly entering the soil nitrogen pool. These findings underscore that even under sustained fertilization regimes, soil nitrogen mineralization remains a dominant contributor to plant nitrogen nutrition, while fertilizer-derived nitrogen is subject to significant immobilization and loss pathways.

Nitrogen losses are further exacerbated by volatilization and other atmospheric processes, particularly when fertilizer application rates are poorly synchronized with crop demand. Recent assessments indicate that emission rates are strongly influenced by fertilizer rate, nitrogen form, and soil moisture conditions, with disproportionately high N₂O emissions occurring under excess nitrogen supply or unfavorable soil conditions[9,11].

In addition to gaseous emissions, mineral fertilization enhances nitrogen losses through leaching and runoff, especially in high-input systems and in regions characterized by high rainfall or intensive irrigation. These losses reduce nutrient use efficiency and contribute to downstream environmental impacts, including groundwater contamination and eutrophication of surface waters [10].

Taken together, the evidence clearly indicates that the environmental externalities of conventional mineral fertilization extend well beyond the field scale. Recent reviews converge in emphasizing that mitigating carbon and nitrogen losses requires a shift away from purely input-intensive fertilization strategies toward management approaches that enhance nutrient retention, improve soil organic matter dynamics, and better align nitrogen availability with crop demand [3,13].

These contrasting soil carbon and nitrogen pathways under mineral and organic fertilization regimes are conceptually summarized in Figure 2, highlighting their divergent long-term implications for soil functioning and greenhouse gas emissions

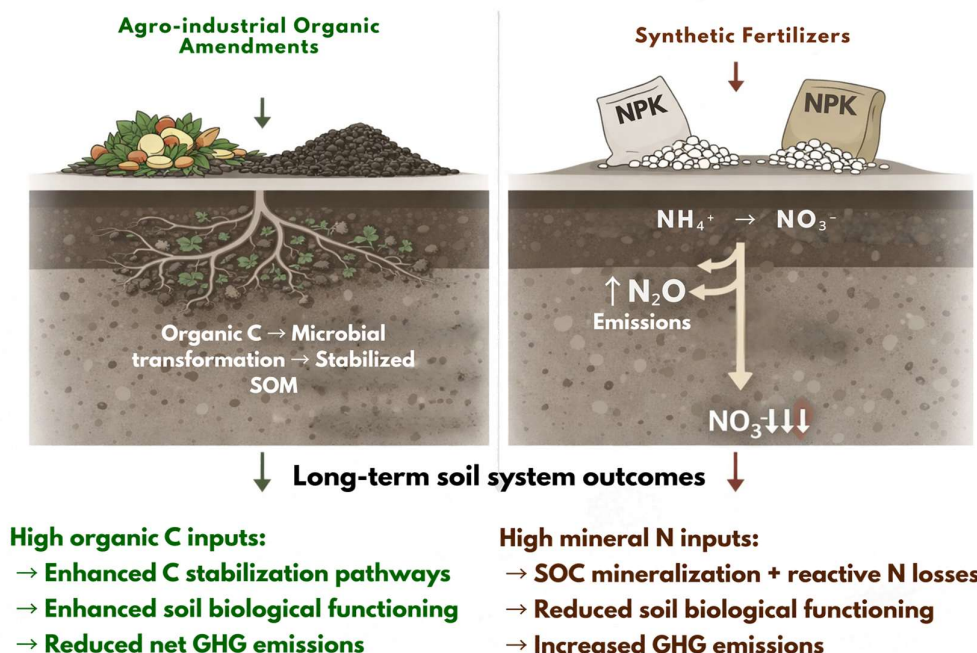


Figure 2. Conceptual comparison of soil carbon and nitrogen dynamics under agro-industrial organic amendments and synthetic mineral fertilizers.

5. Organic Amendments from Agro-Industrial Residues as Tools for Soil Stewardship

Agro-industrial activities generate very large quantities of organic residues, estimated at approximately 1.3 billion tons per year worldwide [74,75]. At present, a substantial fraction of these residues is still managed through disposal routes such as landfilling or incineration, which are associated with significant environmental, economic, and social drawbacks. Improper management of agro-industrial wastes promotes uncontrolled microbial decomposition processes, leading to greenhouse gas emissions, release of potentially toxic degradation products, and the proliferation of pathogenic microorganisms [76].

Recent assessments indicate that the carbon footprint associated with agro-industrial waste streams is far from negligible. Capanoglu et al. [77], estimated that emissions linked to food and agro-industrial waste mismanagement correspond to an annual accumulation of approximately 3.3 billion tons of CO₂-equivalent in the atmosphere. In addition to climate impacts, the uncontrolled release of pollutants from these residues contributes to air quality deterioration, with documented implications for human health, including respiratory disorders [78]. Beyond environmental concerns, the socio-economic dimension of agro-industrial waste is equally critical. The global economic cost of food waste alone has been estimated at around 1000 billion USD per year, underscoring the inefficiency of current linear production–consumption systems [77]. These challenges are particularly

pronounced in developing regions, where technological and infrastructural limitations constrain the implementation of sustainable waste recovery pathways [76].

Despite these issues, agro-industrial residues represent a largely untapped resource with considerable potential for multi-valorization. Owing to their heterogeneous but nutrient-rich composition, these residues can be converted into a wide range of value-added products, including biofuels, biopolymers, enzymes, nutraceuticals, biogas, and biofertilizers [74]. Within agricultural systems, their transformation into organic soil amendments is gaining increasing attention as a strategy to simultaneously address waste management challenges and improve soil functioning.

Organic amendments derived from agro-industrial residues are increasingly framed within soil stewardship approaches, as they contribute to maintaining soil organic matter, enhancing biological activity, and supporting nutrient cycling. Recent studies highlight that soil responses to organic amendments are not solely driven by the quantity of organic matter applied, but strongly depend on feedstock characteristics and processing pathways, which together determine amendment quality and stability [12,79]. In this context, agro-industrial residues constitute a particularly relevant feedstock base, as their valorization into organic amendments enables nutrient recycling while aligning fertilization practices with circular economy principles [14].

5.1. Amendment types, processing pathways, and agro-industrial feedstocks

As widely reported, organic amendments comprise a heterogeneous group of materials derived from agricultural and agro-industrial streams, including composts produced by aerobic stabilization, digestates obtained from anaerobic digestion, and vermicomposts generated through earthworm-mediated processing. These amendments differ substantially in organic matter stabilization degree, nutrient forms, and biochemical composition, leading to contrasting agronomic and environmental effects after soil application [14].

Composts are generally characterized by a higher proportion of stabilized organic matter and a lower share of readily degradable carbon, reflecting extensive microbial transformation during processing. Digestates frequently contain higher proportions of labile organic compounds and mineral nitrogen forms, resulting from the conversion of easily degradable carbon into biogas during anaerobic digestion. Vermicomposts are often described as biologically “enriched” amendments, where earthworm activity and associated microbial processes modify residue composition, potentially enhancing humification, microbial activity, and plant growth-promoting properties [73,79].

Importantly, the literature increasingly highlights that agro-industrial feedstocks (e.g., processing residues, by-products, organic sludges, and crop-processing wastes) can enter different treatment routes (composting, anaerobic digestion, vermicomposting), meaning that processing technology and feedstock must be interpreted jointly when evaluating soil impacts [12].

5.2. Effects on soil organic carbon stocks and carbon stability

A substantial body of evidence indicates that organic amendments can enhance soil organic carbon (SOC) stocks by increasing carbon inputs to agricultural soils. Long-term and repeated applications are frequently associated with SOC accumulation; however, recent studies stress that outcomes vary with amendment type, feedstock composition, soil properties, and climate [3].

Compost-based amendments are often reported to be particularly effective in promoting longer-term SOC stabilization due to their higher share of recalcitrant organic compounds. In contrast, digestate applications are commonly associated with stronger short-term effects on labile carbon pools and microbial activity; SOC responses may therefore be more variable unless stabilization processes efficiently convert amendment-derived inputs into persistent forms. Vermicompost applications are increasingly reported to influence both SOC quantity and quality, enhancing labile and intermediate fractions and potentially supporting the formation of more persistent carbon through biologically mediated transformations[62].

Across amendment types, recent literature increasingly emphasizes that SOC changes should not be interpreted solely through total SOC content. Instead, studies highlight the importance of carbon quality and stabilization pathways, including aggregate protection, mineral association, and microbial transformation, as key determinants of persistence and climate relevance of sequestered carbon [12]. As shown in Table 2, compost-based amendments are generally associated with larger and more persistent increases in soil organic carbon, particularly in long-term field trials, whereas digestate applications often result in smaller or more variable SOC responses over shorter time scales. Vermicompost applications tend to exhibit intermediate effects, frequently enhancing labile and partially stabilized carbon fractions.

Table 2. Soil organic carbon (SOC) responses to compost, digestate, and vermicompost applications derived from agro-industrial residues under different soils, climates, and experimental durations.

Processing	Feedstock	SOC response	Duration	Climate / Location	Study
Composting	10 straw + 90 wet wastes	Increased by +18–35% vs control	190 days	Mediterranean, Italy	[80]
Composting	50 straw + 50 wet wastes	Increased by +25–40% vs control	190 days	Mediterranean, Italy	[80]
Composting	90% waste from olive oil + 10% straw 34% olive mill	Increased by +5–14% vs control	180 days	Mediterranean, Italy	[81]
Composting	Decanter process + 33% buffalo manure and 33% straw.	Increased by +8–13% vs control	180 days	Mediterranean, Italy	[81]
Composting	Organic waste compost	Increased by +23% vs control	18 years	Temperate, China	[82]
Composting	Green waste compost	Increased by 42% control	Long-term	Mediterranean, USA	[83]
Composting	Stabilized organic compost	4.24–6.82 Mg C ha ⁻¹ retained	150 days	Temperate, Italy	[84]
Composting	Poultry manure compost	Increased by +12.6% (21.8 Mg C ha ⁻¹) Increased SOC stock via	19 years	Mediterranean, USA	[85]
Composting	Cow dung	enhanced labile OC and ROC fractions	2 years	Subtropical, China	[86]
Anaerobic digestion (liquid)	Cattle slurry digestate	No significant change; upward trend	4 years	Temperate, Central Europe	[87]
Anaerobic digestion (solid vs liquid)	Separated digestate fractions	Higher SOC with solid digestate	2 years	Temperate, Lithuania	[88]

Anaerobic digestion (solids)	Biogas digestate solids	+3.0 (sandy) and +2.2 Mg C ha ⁻¹ (loamy)	120 days	Temperate, USA	[89]
Anaerobic digestion (modelled)	Crop-residue digestate	Increased by +3.3 Mg C ha ⁻¹ (~5%)	Long-term	Boreal–temperate, Sweden	[90]
Vermicomposting	Organic residues	No significant change vs initial soil	1 year	Tropical, Vietnam	[91]
Vermicomposting	Organic waste	Increase in labile SOC fractions	2 years	Subtropical, India	[52]
Vermicomposting	Organic waste	Increased by +14–90% (dose-dependent) SOC stock	180 days	Laboratory	[92]
Vermicomposting	Cow dung	increased via labile and oxidizable C	2 years	Subtropical, China	[86]

5.3. Impacts on soil biology, functionality, and ecosystem services

Beyond SOC dynamics, organic amendments are widely reported to enhance soil biological functioning, with numerous studies describing increases in microbial biomass, enzymatic activity, and functional diversity following amendment applications. These responses are generally attributed to improved substrate availability and habitat conditions, and they are increasingly considered central indicators of soil stewardship outcomes [16].

Composts and vermicomposts are frequently associated with improved soil biological structure and activity, supporting aggregation processes and nutrient cycling. Vermicomposts, in particular, are often highlighted for their strong effects on microbial activity and soil biological indicators, likely due to the combined influence of earthworm processing and microbial enrichment during vermicomposting [62](Liang X., 2025). Digestates can also stimulate microbial activity, especially in the short term, but several studies note that responses may be transient unless applications are integrated with broader management strategies that support SOC stabilization and balanced nutrient cycling [13].

These biological improvements often translate into functional co-benefits, including improved aggregate stability, water infiltration, and nutrient retention, which collectively contribute to soil resilience under climate variability and environmental stress. This body of evidence reinforces the role of organic amendments—particularly those derived from agro-industrial residues—as multifunctional tools within soil stewardship strategies aimed at sustaining soil health and productivity [16].

6. Circular Fertilization Strategies Based on Agro-Industrial Residues: Carbon Footprint Implications

6.1. Fertilizer carbon footprint as a dominant hotspot in agricultural systems

Life Cycle Assessment (LCA) is the most widely adopted methodological framework for quantifying the climate impacts of agricultural inputs and management practices, as it accounts for greenhouse gas emissions generated along the entire supply chain, from raw material extraction and industrial processing to field application and, where relevant, end-of-life stages [93,94]. Within LCA studies, climate impacts are commonly expressed as Global Warming Potential over a 100-year time horizon (GWP₁₀₀), reported in kg CO₂-equivalents (kg CO₂ eq), integrating emissions of carbon dioxide (CO₂), methane (CH₄), and nitrous oxide (N₂O) into a single indicator.

Across LCA-based assessments, fertilizer production and use are consistently identified as major emission hotspots in agricultural systems. In particular, synthetic mineral fertilizers—and nitrogen fertilizers in particular—exhibit high carbon footprints due to the energy-intensive nature of industrial synthesis processes and associated upstream emissions. The production of mineral nitrogen fertilizers relies heavily on fossil energy inputs, especially during ammonia synthesis, and is further influenced by emissions related to the extraction and processing of phosphorus and potassium raw materials [95]. Reported emission factors for mineral nitrogen fertilizer production typically range between 2.0 and 2.5 Mg CO₂-eq per Mg of N, confirming fertilizer manufacture as one of the dominant contributors to the carbon footprint of the agri-food supply chain [96,97].

More detailed LCA studies highlight that not only fertilizer quantity but also fertilizer formulation and ingredient selection substantially affect climate impacts. Hasler et al. [95] demonstrated that greenhouse gas emissions associated with fertilizer production vary markedly among different fertilizer product types (FPTs), primarily due to differences in nitrogen sources and processing pathways. For complex fertilizers with a nutrient composition of 17-5-13, total emissions ranged between 487 and 560 kg CO₂-eq per functional unit, with complex fertilizers exhibiting significantly higher emissions compared with blended products. In contrast, fertilizers based on urea combined with muriate of potash (MOP) and triple superphosphate (TSP), or on calcium ammonium nitrate (CAN) combined with MOP and diammonium phosphate (DAP), showed lower emissions, around 488–498 kg CO₂-eq.

Similarly, fertilizers with a balanced nutrient composition (15-15-15) generally displayed lower climate impacts, with emissions ranging from 391 to 524 kg CO₂-eq, depending on ingredient selection [95]. In this case, urea-based formulations again resulted in the lowest emissions, approximately 391 kg CO₂-eq, whereas CAN-based products showed substantially higher values. Differences exceeding 130 kg CO₂-eq were reported between alternative formulations providing the same nutrient ratios, underlining that fertilizer design choices alone can significantly influence greenhouse gas emissions.

These findings consistently indicate that mineral fertilization represents a structurally high-emission baseline within agricultural systems. Even when optimized formulations are selected, synthetic fertilizers remain intrinsically carbon-intensive due to their dependence on fossil energy and industrial processing. Against this background, fertilization strategies based on recycled nutrients and agro-industrial residues are increasingly explored within LCA frameworks as potential pathways to reduce the carbon footprint of crop production, providing the reference context for the comparative assessment of organic fertilization systems discussed in the following sections.

6.2. Carbon footprint of organic fertilization pathways: quantitative evidence from LCA studies

LCA studies assessing composting, anaerobic digestion, and vermicomposting of agro-industrial residues report a wide range of GWP values, reflecting differences in processing technologies, feedstocks, functional units, and assessment boundaries (Table 3).

Anaerobic digestion (AD) systems evaluated on a mass-based functional unit typically report GWP values between 64.7 and 228 kg CO₂-eq per ton of manure, depending on system configuration and boundary definition [76,98,99]. When impacts are expressed per unit of useful energy, substantially lower values are observed, such as 0.28 kg CO₂-eq per kWh of electricity produced [100] or 0.034 kg CO₂-eq per MJ of biomethane [101]. These results highlight the critical role of energy substitution credits in shaping the overall carbon footprint of AD systems. Additional variability arises from digestate management strategies, including liquid versus solid fractions and integrated composting steps [82,99].

Composting systems display even greater variability in reported GWP values. Pilot-scale composting chains based on agricultural residues in Mediterranean contexts show relatively low impacts, ranging from 37.45 to 39.05 kg CO₂ eq per ton of compost [102]. In contrast, full-scale facilities or alternative system boundaries yield higher values, including 92.6 kg CO₂-eq per ton for passively aerated composting of olive mill waste [103] and 130 kg CO₂-eq per ton in district-scale composting systems [104]. Technology-specific comparisons further demonstrate that composting configuration affects emissions, with reported values of 63.9 kg CO₂-eq per ton for tunnel composting and 63.15 kg CO₂-eq per ton for confined windrow systems [105], while home composting shows intermediate impacts around 82.6 kg CO₂-eq per ton [106].

Vermicomposting is less extensively represented in LCA literature but generally exhibits comparatively low climate impacts when expressed per unit of product. For example, a cradle-to-gate assessment of vermicompost derived from grape marc reported a GWP of 0.2 kg CO₂-eq per kg of vermicompost [107]. A recent study shows that vermicompost is the most climate-friendly amendment (25 kg CO₂ eq ton⁻¹), compared with compost and digestate [108]. The evidence summarized in Table 2 clearly indicates that the carbon footprint of circular fertilization pathways cannot be generalized without explicit consideration of methodological assumptions. Differences in functional units (e.g., per ton of waste, per unit of energy, or per unit of agricultural output) fundamentally alter interpretation, as mass-based indicators emphasize waste treatment performance, whereas energy- or product-based indicators capture substitution and productivity effects.

Similarly, system boundaries strongly influence reported GWP values by determining whether avoided emissions, downstream treatment stages, or co-product credits are included. As a result, the wide ranges reported for composting, anaerobic digestion, and vermicomposting systems reflect not only technological diversity but also structural differences in LCA modelling approaches.

Overall, while LCA evidence supports the potential of agro-industrial residue valorization to reduce reliance on carbon-intensive mineral fertilizers, climate mitigation outcomes depend primarily on process design, scale, residue characteristics, and assessment framework, rather than on the organic nature of the fertilizer alone.

Table 3. Overview of Life Cycle Assessment studies reporting Global Warming Potential (GWP) of composting, anaerobic digestion, and vermicomposting systems used for organic fertilization.

Functional Unit	System boundaries	Scale	Technology	GWP (kg CO ₂ eq)	Reference
1 ton of wet manure	cradle to gate	Full-scale	anaerobic digestion	228	[98]
1 ton of product (dry matter)	cradle to gate	Full-scale	crop activity	0.38	[109]
1 ton of compost	Cradle to gate	Full-scale	Composting	43	[108]
1 ton of digestate	Cradle to gate	Full-scale	anaerobic digestion	110	[108]

1 ton of vermicompost	Cradle to gate	Full-scale	vermicomposting	25	[108]
1 kg of vermicompost	cradle to gate	Full-scale	vermicomposting	0.2	[107]
1 ton of pig manure	Cradle to gate	Full-scale	anaerobic digestion	78.15	[110]
1 kg of refined rice packed	Cradle to gate	Full-scale	anaerobic digestion	1.86	[111]
1 MJ	Cradle to gate	Full-scale	anaerobic digestion	0.034	[101]
CO ₂ -eq/kg Fat and Protein Corrected Milk	Cradle to gate	Full-scale	anaerobic digestion	1.3	[112]
1 ton of woodchips	Cradle to gate	Full-scale	combustion, pyrolysis	300	[113]
1 MWh of net electricity and heat co generated in a biogas plant	Cradle to grave	Full-scale	anaerobic digestion	232	[114]
1 kWh of useful energy (heat and electricity)	Cradle to grave	Laboratory	anaerobic digestion	0.051	[115]
1 ton of slurry	Cradle to gate	Full-scale	Acidification	5250	[116]
1 ton of waste	Cradle to grave	Full-scale	anaerobic digestion, composting	1081	[117]
1 ton of poultry litter	Cradle to grave	Full-scale	anaerobic digestion, pyrolysis, gasification, hydrothermal carbonization	657	[118]
1 ton of AFRs (agricultural and forest residues)	Cradle to grave	Pilot	Composting	1.88	[119]
1 kWh of electricity produced	Cradle to gate	Full-scale	anaerobic digestion	0.28	[120]
1 ton of dry matter biomass	Cradle to gate	Full-scale	anaerobic digestion, pyrolysis	244	[121]
1 ton of ready-to-use material (peat or compost)	Cradle to grave	Full-scale	Composting	92.6	[122]
1 ton of pig manure	Cradle to grave	Full-scale	anaerobic digestion, composting	64.7	[99]
1 Kg manure, 1 m ³ biogas	Cradle to gate	Full-scale	anaerobic digestion	0.14	[123]

1 ha of maize crop	Cradle to grave	Full-scale	anaerobic digestion, nitrogen stripping	3354	[100]
1 ton of wheat grain	Cradle to gate	Full-scale	Composting	1333	[124]
1 kg of OFMSW	Cradle to grave	Pilot	composting, anaerobic digestion, composting + anaerobic digestion	22.57	[125]
1 ton of compost	Cradle to gate	Pilot	windrows composting	39.05	[102]
1 ton of compost	Cradle to gate	Pilot	windrows composting	37.45	[102]
1 ton of compost	Cradle to gate	Pilot	Composting	130	[104]
1 ton of compost	Cradle to gate	Pilot	tunnel composting	63.9	[105]
1 ton of compost	Cradle to gate	Pilot	confined windrows composting	63.15	[105]
1 ton of compost	Cradle to gate	Pilot	Home composting	82.6	[106]

7. Implications for Climate Policy, Carbon Markets, and Soil-Based Natural Climate Solutions

The growing scientific evidence reviewed in this study positions soil stewardship not only as an agronomic and environmental strategy, but also as a central component of emerging climate policy instruments and carbon market mechanisms. As agricultural emissions remain difficult to abate through technological substitution alone, increasing attention is being directed toward land-based mitigation options capable of delivering measurable, scalable, and cost-effective climate benefits.

7.1. Soil Stewardship within Climate Policy Frameworks

Recent climate policy frameworks increasingly recognize agricultural soils as strategic assets for mitigation and adaptation [126]. International initiatives promoted by the IPCC, FAO, and UNFCCC now explicitly frame soil carbon management as part of broader Natural Climate Solutions (NCS), alongside afforestation, wetland restoration, and improved land management [127]. Within this context, fertilization practices based on organic amendments are no longer viewed solely as waste management or soil fertility tools, but as potential contributors to national greenhouse gas mitigation targets [96].

At the European level, policy instruments such as the European Green Deal, the Farm to Fork Strategy, and the EU Soil Strategy for 2030 increasingly promote reductions in synthetic fertilizer use, enhanced nutrient recycling, and improvements in soil organic carbon stocks [128]. The Common Agricultural Policy (CAP) has begun integrating these objectives through eco-schemes and agri-environment-climate measures, although implementation remains largely practice-based rather than outcome-based [129].

7.2. Carbon Credits, Carbon Farming, and Soil-Based Offsets

In parallel with regulatory policies, voluntary and compliance carbon markets have rapidly expanded their interest in soil-based mitigation pathways [130]. Carbon farming schemes increasingly include practices such as organic fertilization, compost application, and digestate recycling among eligible activities, based on their potential to reduce emissions associated with mineral fertilizer production and to enhance soil carbon stocks [131].

However, the literature reviewed highlights that the role of organic fertilization in carbon credit generation is complex and highly context-dependent [132]. While Life Cycle Assessment studies consistently show lower carbon footprints for circular fertilization pathways compared with synthetic fertilizers, translating these reductions into tradable credits requires robust Monitoring, Reporting and Verification (MRV) frameworks [133]. Key challenges include the attribution of emission reductions to specific practices, the definition of appropriate baselines, and the treatment of indirect effects such as avoided waste emissions and nutrient substitution [134].

Soil organic carbon sequestration is increasingly proposed as a measurable climate benefit within carbon markets, yet scientific evidence underscores that SOC gains vary widely across systems and are influenced by soil type, climate, amendment characteristics, and management duration [135]. Issues of additionality, permanence, and reversibility therefore remain central to the credibility of soil-based carbon credits. Recent methodological developments emphasize conservative accounting approaches and long-term commitments to address these uncertainties, rather than assuming uniform sequestration rates [136].

7.3. Beyond Carbon: Natural Capital and Environmental Credits

Beyond carbon credits alone, fertilization strategies based on agro-industrial residues are increasingly discussed within broader natural capital and environmental credit frameworks [70]. These include emerging markets for ecosystem services related to soil health, nutrient retention, biodiversity enhancement, and reduced nutrient losses to water bodies [4]. Organic amendments have been shown to improve soil structure, biological activity, and nutrient cycling, supporting multifunctional outcomes that extend beyond climate mitigation [137].

In this perspective, soil stewardship aligns with the transition from single-metric carbon accounting toward multi-benefit climate-smart agriculture, where carbon footprint reduction, soil resilience, and resource circularity are jointly valued. Although these natural credit schemes are still under development, the scientific evidence synthesized in this review supports the inclusion of circular fertilization practices as enabling measures within integrated sustainability frameworks.

8. Conclusions

This review critically synthesizes current scientific evidence on soil stewardship strategies aimed at mitigating carbon emissions and enhancing environmental sustainability in agricultural systems, with a particular focus on fertilization practices grounded in circular economy principles. The literature consistently identifies fertilization management as a dominant driver of agricultural greenhouse gas emissions, with synthetic mineral fertilizers—especially nitrogen fertilizers—representing one of the most carbon-intensive inputs across agri-food systems. Life Cycle Assessment studies demonstrate that composting, anaerobic digestion, and vermicomposting of agro-industrial residues can significantly reduce the carbon footprint associated with fertilization, although reported impacts vary widely depending on system boundaries, functional units, technologies, and scales of implementation. These findings emphasize that climate mitigation outcomes are process- and context-specific, rather than inherent to organic fertilization per se. Beyond emission reductions, organic amendments contribute to improve soil organic carbon stocks and soil functioning, reinforcing the role of soils as multifunctional components of agroecosystems. While soil carbon sequestration is increasingly incorporated into carbon footprint and carbon market frameworks, the evidence reviewed highlights substantial uncertainty related to magnitude, persistence, and attribution of SOC gains, underscoring the need for conservative accounting and robust monitoring approaches. Overall, soil stewardship strategies based on circular fertilization emerge as scientifically

credible and policy-relevant pathways within the evolving landscape of climate mitigation, carbon farming, and natural capital markets. Future research efforts should focus on long-term field experiments in conjunction with standardized LCA and MRV approaches, thereby enhancing the scientific foundation for soil-based climate solutions and facilitating their credible integration into climate policies and environmental credit frameworks

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