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Straw Versus Manure in Soil Organic Carbon Sequestration: Mechanisms, Efficiency and Synergies for Sustainable Agriculture: A Review

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Review Article

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ABSTRACT

Soil organic carbon (SOC) sequestration is a key strategy for mitigating climate change and enhancing agricultural sustainability. This review carefully compares straw and manure, which are both commonly used to increase SOC levels, by explaining how they work differently, their effectiveness, and their real-world effects. Although both manure and straw enhance SOC, the latter

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is more efficacious due to its robust constituents (such as lignin) and nutrient density, which foster enduring humus development and microbial activity, resulting in a 32–50% augmentation of SOC stocks. Straw breaks down quickly and has a high carbon-to-nitrogen (C:N) ratio, which helps soil clump together; however, it needs to be used for a long time (more than 20 years) and managed carefully (like being buried deep at 35 cm) to noticeably increase SOC levels by about 16%. Significant differences in decomposition dynamics indicate that manure retains 45–58% of its carbon after one year, but straw retains just 27–48% due to accelerated mineralization rates. The amalgamation of manure and straw has synergistic effects that enhance carbon sequestration efficacy by 39.9%, prolong the carbon residence time below the surface by 20–30 days, and elevate crop yields by as much as 70.4% compared to individual applications. Although manure entails elevated handling expenses, it provides superior nutrient recycling and enhances soil health. Straw, on the other hand, has lower initial costs but, for practical and financial reasons, comes with the risk of long-term nutrient depletion. Case studies show that using combined methods works well, especially in dry and salty soils, where these methods can improve crop yields by 10–44%. Future work should focus on long-term field studies, understanding how microbes interact, and creating specific strategies for different regions to make the best use of modification techniques. This review advocates for the tailored incorporation of straw and manure into climate-smart agriculture models to improve SOC storage, resilience, and food security.

Keywords: Straw; manure; carbon sequestration; sustainable agriculture.

1. INTRODUCTION

Carbon sequestration is referred to as the process of transporting carbon from the atmosphere to the soil via plants or other organisms, where it is kept as soil organic carbon, leading to an increase in global carbon stockpiles in the soil (McCarthy, 2001; Basile-Doelsch et al., 2020). The capacity for carbon sequestration differs among various landscapes and land uses. Forests, grasslands, and rangelands trap around one-quarter of global carbon emissions. According to estimates, in 25 years, soils might store around 20 Pg C, exceeding 10% of anthropogenic emissions (Tebeje, 2020; Blair, 2021). The worldwide carbon reservoir to a depth of one meter is estimated at 2500 Pg C, of which around 1500 Pg C is SOC, over 3.2 times larger than the atmospheric carbon pool and four times that of the biotic carbon pool (Karelin, 2015; Blakemore, 2024).

Consequently, many climate-smart agricultural methods are required and advocated to improve agricultural output and guarantee food security (Jamil et al., 2023; Wakweya, 2023) Carbon sequestration in soil means capturing and storing carbon dioxide (CO_2) from the air into the soil, which helps keep it there longer and reduces the amount that gets released back into the atmosphere. The objectives of soil carbon sequestration include (1) mitigating anthropogenic emissions from deforestation, fossil fuel combustion, and cement production; (2) decreasing the net increase in atmospheric CO_2 concentration and its pool (800 PgC); (3) restoring soil organic carbon concentrations to levels exceeding the 1.5–2.0% threshold; (4) enhancing and sustaining agronomic productivity while promoting food and nutrient security; (5) optimizing input utilization in managed ecosystem soils; (6) fostering climate-resilient soils and agro-ecosystems; and (7) diminishing the risks of non-point source pollution and accelerated erosion (Rodrigues et al., 2023; Tian et al., 2023; Villat & Nicholas, 2024; Nazir et al., 2024).

When natural ecosystems change to agricultural systems, less biomass-C from things like roots and fallen leaves, along with more erosion and leaching of dissolved organic C, reduces the amount of SOC stored in the soil. The SOC stock may be diminished by 30–75% depending on the degree, severity, and type of degradation. Soils susceptible to erosion and other degrading processes, including loss of cohesion, structural stability, erosion, or compaction, have become increasingly depleted of their compromised SOC reserves (Cornejo et al., 2023).

Both manure and straw applications are excellent methods for increasing soil organic carbon (SOC) stocks; however, manure yields greater increases, particularly when used in conjunction with mineral fertilizers (Huang et al., 2022; Zhu et al., 2023). Using manure boosts soil organic carbon (SOC), especially in cooler areas and in clay or acidic soils, with the biggest increases seen in the top 15–20 cm of soil, although changes can also be found deeper down. Farmyard, cattle, and pig manure produce the most significant increases in SOC up to 50% for farmyard manure by directly contributing carbon and promoting plant growth, thereby augmenting crop residue and root inputs (Bai et al., 2023).

State of Charge SOC improvements are more significant when the beginning SOC is low (below 1%); however, absolute increments are larger when the starting SOC is elevated. In contrast, straw return also improves SOC, yielding an average increase of around 16% and a sequestration rate of 0.26 g/kg/year, exhibiting more pronounced effects in colder, drier climes, carbon-rich and alkaline soils, and with more straw inputs (Huang et al., 2022; Wu et al., 2023). The introduction of straw enhances microbial biomass and activity, thereby facilitating the accumulation of SOC, particularly in tropical and warm climates. Prolonged and elevated straw application results in increased soil organic carbon buildup (Wu et al., 2019 Jin et al., 2020; Wang et al., 2021). Both amendments trap carbon and enhance soil health, structure, and resilience, with their efficacy contingent upon climate, soil type, baseline SOC levels, and management techniques. Our objective in this work to compare the role both straw and manure for affecting soil organic carbon sequestration: mechanisms, efficiency, and synergies for sustainable agriculture.

2. CARBON SEQUESTRATION PROCESSES: HOW STRAW AND MANURE DIFFER

Organic amendments such as straw and manure improve soil carbon sequestration via unique but complementary methods. Straw mainly provides easily broken down carbon that mixes into soil clumps, which helps protect it from breaking down too quickly; importantly, how deep the straw is buried matters burying it deeper (35 cm instead of 15 cm) increases the amount of carbon kept from the straw by 4.1% and extends how long it stays in the soil by 15 days. However, to achieve significant improvements in SOC stability, it usually requires applying it for more than 20 years. Manure contains strong organic materials like lignin that help create stable humus and increase microbial activity, which supports the formation of clumps, and the stability of organic matter linked to minerals. The amalgamation of manure with straw elevates total nitrogen content by 12–18% and prolongs carbon residence duration in subsurface layers by 20–30 days relative to the use of straw alone (Ge et al., 2021; Wang et al., 2021).

Combining manure with deep straw burial (35 cm) is especially effective, achieving a carbon storage efficiency of 39.9% compared to 35.8% with shallow burial, and resulting in 23.8% increase in soil organic carbon than using either one alone; importantly, alkaline soils and dry climates show even stronger bene fits from this combination. Straw and manure exhibit considerable differences in their processes and results regarding carbon sequestration. Straw adds easily broken-down carbon that mixes into soil for protection, while manure adds tough chemicals like lignin that help form stable humus. When straw is buried deeper (35 cm), it helps keep carbon in the soil better by 4.1% and keeps it there for 15 more days compared to burying it shallowly, while manure increases microbial activity, which helps form soil clumps and stabilize organic matter linked to minerals. Long-term studies show that using straw for more than 20 years is needed to really stabilize SOC, while mixing manure with straw increases total nitrogen by 12–18% and keeps carbon in the subsoil for 20–30 days longer than using straw alone. In terms of efficiency, the amalgamation of manure and deep straw burial attains a carbon sequestration efficiency of 39.9%, surpassing shallow burial at 35.8%, and yielding a 23.8% greater increase in soil organic carbon compared to the use of either amendment in isolation (Thompson et al., 2019; Olayemi, 2021; Wang et al., 2021; Achtymichuk, 2024; Yadavet al., 2025).

Straw and manure exhibit significant differences in their decomposition dynamics: straw decomposes more rapidly, with 70–87% of its organic carbon categorized as easily decomposable, in contrast to 57–83% for manure; its labile carbon degrades at rates of 1.0–4.9% annually—almost five times faster than manure's 0.7–1.1% (DeJin et al., 2023). Conversely, the higher levels of lignin and resistant materials in manure lead to a slower breakdown and more stable humus formation. After one year, carbon retention results indicate that 27–48% of straw carbon persists in the soil, contingent upon its type and burial depth, whereas manure retains 45–58% of its carbon. Despite the rapid initial decomposition of straw, deeper burial (35 cm) enhances retention by 4.1% and prolongs its mean residence time by 15–31 days (Wang et al., 2021). The synergistic effects of integrating manure with straw augment sequestration efficiency: manure mitigates the swift decomposition of straw, resulting in a 12–18% increase in total nitrogen and prolonging subsoil carbon residence time by 20–30 days, with combined applications achieving a carbon sequestration efficiency of 39.9% compared to 35.8% for straw alone (Sahoo, 2022; Wang et al., 2021). Manure presents multiple advantages over straw for carbon sequestration: it leads to a significant increase in SOC stocks approximately 35.4% on average demonstrating consistent effects across various soil depths, climates, and types; it facilitates prolonged carbon residence times by stabilizing carbon within aggregates and micro-aggregates; it enhances soil fertility by supplying not only carbon but also vital nutrients (notably nitrogen), which promote plant growth, elevate crop yields, and augment carbon inputs to the soil; it improves carbon stability, as recalcitrant compounds such as lignin contribute to the formation of more stable humus, rendering the stored carbon less susceptible to decomposition; and it generates a beneficial synergy when combined with straw, further improving SOC stability and nitrogen retention in both surface and subsoil layers (Kumar et al., 2013; Berhane et al., 2020; Kavya et al., 2023).

The long-term application of manure and straw yields several synergistic advantages: it markedly enhances SOC storage, with studies indicating SOC increases exceeding 30%; it augments soil fertility and nutrient cycling by elevating total nitrogen and phosphorus levels, improving nutrient retention, and mitigating nutrient leaching, thereby sustaining crop productivity; it results in higher and more consistent crop yields, even under adverse weather conditions, due to improved soil structure and moisture retention; it improves soil structure and water management by promoting aggregation and increasing water-holding capacity, while reducing evaporation and runoff, which is vital for resilience in arid or variable climates; and it fosters microbial activity, as the combination of organic materials nurtures a diverse and active microbial community that accelerates organic matter decomposition and further stabilizes carbon in the soil (Takakai et al., 2020; Gross & Glaser, 2021).

3. ANALYZING THE CARBON INPUT AND RETENTION OF STRAW AND MANURE

The amount, caliber, and duration of carbon inputs from straw and manure exhibit unique patterns that influence their efficacy in augmenting SOC. Straw usually adds about 3 tons of carbon per hectare to the soil, which is around 28% of the total carbon from aboveground sources; however, only a small part of this carbon from straw is kept as SOC (Dannehl et al., 2017). Manure from farms, especially from cows and pigs, adds a lot of carbon to the soil and usually increases SOC levels more than straw does, with manure boosting SOC by 32–50%, depending on the type of manure and how it's managed. The quality of carbon is quite different: straw has a wide C:N ratio and high lignin content, making it low in nitrogen and slower to break down at first. However, only about 2.6% of the carbon from straw stays in the soil stable SOC, while most of it is lost during the breakdown process.

In contrast, manure has more organic matter that breaks down quickly and contains important nutrients, especially nitrogen, and its lower carbon-to-nitrogen ratio encourages more microbial activity, which helps turn manure carbon into stable soil organic carbon more effectively. When it comes to how long it lasts and stays in the soil, straw carbon does not remain stable for long; many studies show it has little impact on the overall amount of SOC, with only a small part becoming stable as mineral-associated organic carbon (MAOC) or particulate organic carbon (POC). Furthermore, root-derived carbon contributes two to three times more to SOC than straw inputs.

Alternatively, manure leads to larger and longer-lasting increases in SOC, affecting deeper layers of soil and staying effective across different soil types and weather conditions. Carbon from manure is more easily captured in soil clumps and turned into humus, which helps keep it in the soil for a long time, making manure a very effective way to improve and maintain soil organic carbon over time (Xu et al., 2019; Benbi & Brar, 2021). The comparison is summarized in Table 1. The longevity of carbon from straw and manure in soil is influenced by several critical elements, starting with the quality of the organic material itself. Straw has a high C/N ratio of about 67 for wheat and 50 for maize, which slows down its breakdown and reduces nitrogen availability, making it harder for the carbon from straw to turn into stable SOC (Liang et al., 2023; Hua et al., 2024). By contrast, manure has a lower average C/N ratio of about 22 and contains strong materials like lignin and polyphenols, which help it break down and form stable SOC complexes (Table 2). Soil characteristics are important; having more clay and a good balance

Table 1. Comparison of carbon input, quality, soil organic carbon retention, and persistence between straw and manure amendments

Aspect	Straw	Manure
Carbon Input	Moderate (1.2Mg C $ha^{-1}year^{-1}$)	High (varies by type, more)
Carbon Quality	Wide C:N, high lignin, N-poor	Narrow C:N, nutrient-rich
SOC Retention	Low (≈2.6% of input retained)	High (32–50% SOC increase possible)
Persistence	Short-lived, minimal long-term SOC	Long-lived, persistent SOC increases

Table 2. Comparing the biochemical characteristics, microbial Impacts, decomposition, and Soil interactions of straw and manure Inputs

Factor	Straw	Manure
C/N Ratio	High (slow decomposition)	Low (faster, more stable SOC)
Resistant Compounds	Fewer	More (lignin, polyphenols)
Microbial Effects	Less diversity, slower stabilization	Greater diversity, enhanced stabilization
Soil Interaction	Limited by structure and N availability	Enhanced by clay, pH, and nutrients

of carbon-to-nitrogen ratios helps keep carbon stable and stored, especially from manure, while soil pH and density also impact how microbes work and how well added carbon is stabilized. The way microbial communities work affects the types and variety of soil bacteria and fungi, which in turn impacts how well carbon from straw and manure breaks down and becomes part of stable soil organic carbon; importantly, manure boosts the number and variety of microbes, helping to keep more carbon in the soil. Most of the carbon from straw breaks down quickly, with about 42% to 79% being mineralized, but only around 10% becomes stable soil organic carbon because it breaks down slowly and does not stabilize well, which limits how long it lasts (Su et al., 2020). Manure, on the other hand, helps create stable SOC better because it directly adds strong organic materials and helps produce MAOC. Environmental and management factors, including erosion, sediment transport, and slopes, can physically eliminate organic carbon from the site, thereby diminishing its persistence. At the same time, weather conditions and how land is managed over many years affect carbon levels; over time, the chemical makeup of straw leftovers usually becomes more similar, lessening initial differences, while manure continues to strongly support soil organic carbon.

4. IMPACT ON SOIL ORGANIC CARBON STOCKS

The influence of straw and manure on SOC stores varies significantly in both short-term and long-term scenarios. In the short term, adding straw to the soil can increase SOC levels, especially when used with conservation tillage or kept at the right moisture levels (15–22.5%); (Table 3) traditional mixing or burying straw in ditches also helps boost SOC, but the increases are usually small and depend a lot on how the soil is managed (Han et al., 2018). In contrast, using manure leads to quicker and larger increases in SOC, especially in the top layer of soil (0–20 cm), with studies showing significant SOC growth within a few years, particularly in cooler areas and soils that are mostly clay. In the long run, straw application consistently increases SOC, but its accumulation rate is slower than that of manure. The advantages are more pronounced in reduced- or no-tillage systems and when the straw is thoroughly integrated. Manure, conversely, guarantees sustained and significantly enhanced SOC accumulation over time; meta-analyses consistently indicate SOC stock increases of 32–50% following the application of farmyard, cattle, or pig manure, whereas straw or green manure alone yields only modest long-term enhancements (Li et al., 2023). Additionally, manure not only raises the amount of SOC but also improves its stability and ability to stay in deeper layers of soil, doing better than straw for both short- and long-term SOC buildup in the top and lower soil layers. Significantly, the amalgamation of manure and straw, or their integration with mineral fertilizers, enhances SOC accumulation and stability, presenting a synergistic approach for optimizing SOC storage and promoting long-term soil health.

Table 3. Stability, depth effects, and short- and long-term soc gains comparatively between straw and manure amendments

Amendment	Short-Term SOC Gain	Long-Term SOC Gain	SOC Stability	Depth of Effect
Straw	Moderate	Slow, steady	Moderate	Mostly surface
Manure	High	Sustained, large	High	Surface & deep

5. ROLE OF MICROBIAL ACTIVITY IN DECOMPOSITION AND STABILIZATION

Because of their different chemical compositions and nutritional profiles, straw and manure undergo different microbial processing that affects carbon stabilization in soil, microbial community dynamics, and decomposition rates. Although its high C/N ratio and low nutrient content limit microbial growth and slow decomposition rates, microbial activity especially that of bacteria and fungi who secrete important enzymes such as cellulase and ligninase to break down cellulose, hemicellulose, and lignin drives most straw decomposition (Shaghaleh et al., 2023). Adding nitrogen fertilizer or special bacteria that help break down straw can significantly enhance the activity of microbes and speed up the breakdown of straw, while using groups of microbes or specific microbial agents can also help improve degradation and nutrient recycling. Adding straw to composting systems increases aeration and enhances the growth of aerobic bacteria and thermophilic fungi, thereby improving overall breakdown efficiency (Chen et al., 2024; Mageghwaran et al., 2024).

Manure, with its lower C/N ratio and higher nutrient profile, supports a varied and plentiful microbial community from the onset through microbial successions of Proteobacteria, Actinomycetes, and Bacillus that effectively mineralize organic matter and fix carbon. Adding straw to manure compost enhances microbial diversity and activity, thereby improving the compost quality and decomposition rates. Manure decomposition results in faster organic matter turnover and greater stabilization of organic carbon than straw. Crucially, straw depends mostly on enzyme-driven microbial activity and is constrained by nutrient availability; manure offers a nutrient-rich environment that maintains a larger and stronger microbial community, resulting in both increased initial carbon losses and more long-term carbon stabilization. Combining straw and manure or their composts uses their respective advantages to encourage higher microbial activity, variety, and carbon stabilization. In the high-carbon, low-nitrogen environment of straw, the types of microbes and their activity during straw breakdown are affected by factors like soil pH, nutrients, and moisture; bacteria are more common at first, while fungi increase later. Conversely, the nutrient-rich environment in manure compost promotes rapid microbial development, mostly driven by aerobic bacteria and thermophilic fungus, especially when straw is included for better aeration. The C/N ratio is very important for managing how microbes work and how nitrogen moves: straw has a high C/N ratio (like wheat straw at about 80:1), which causes microbes to use up nitrogen from the soil to meet their needs, slowing down decomposition and possibly leading to temporary nitrogen shortages for plants; on the other hand, manure has a lower C/N ratio (20:1–30:1), which helps microbes break down material efficiently without needing to use up extra nitrogen, leading to quicker decomposition and more nitrogen available for plants. Low C/N inputs like manure (less than 20:1) help with mineralization, while high C/N inputs like straw (more than 35:1) encourage immobilization; C/N ratios in the middle range (20–30:1) keep a balance between these two processes (Table 4). So, to get the best results in microbial activity, nutrient cycling, carbon stabilization, and overall crop yield, it is important to carefully manage the C/N ratio of what you add to the soil.

Table 4. Microbial activity effect and typical C/N Ratio under straw and manure

Material	Typical C/N Ratio	Microbial Activity Effect
Straw	High (>35:1)	Slow decomposition, N immobilized
Manure	Low (~20–30:1)	Fast decomposition, N mineralized

6. ECONOMIC AND PRACTICAL CONSIDERATIONS FOR FARMERS

Practical and financial considerations significantly influence farmers' decisions to utilize straw or manure, with cost, accessibility, and practicality being major issues. The value of straw lies in its nutrient composition and contribution of organic matter; for instance, a 1,200-pound bale of cornstalk straw possesses an estimated fertilizer value of about $27, and when factoring in raking and baling, the total value increases to about $45.25 per bale. Selling prices may reach as low as $1 per 35-pound bale; however, the actual economic value must account for the depletion of organic matter and nutrients from the soil, thereby impacting subsequent crop yields (Deviney et al., 2020; Houser, 2022). Particularly, baling and harvesting add additional expenses to the total cost. Conversely, the value of manure mostly pertains to its nutritional composition, particularly nitrogen, phosphorus, and potassium, which may be quantified using agricultural tools like the University of Minnesota calculator. The average value of manure is approximately $30.25 per ton, with application costs adding an additional $3.25 per ton, resulting in a total of $33.50 per ton (Abebe et al., 2020; Hand, 2024) (Table 5).

However, because of the substantial weight of manure and its elevated water content, which increases handling expenses, the expenditures associated with transportation and application are significant. Despite being less restricted, accessibility remains inconsistent. Straw is typically readily accessible in grain fields as a byproduct of cereal crops and necessitates equipment for baking and transportation. Conversely, manures are primarily available to cattle producers or individuals near livestock operations; transporting them over long distances is frequently uneconomical due to their bulk and low nutrient density; additionally, their application, particularly fresh manure on food crops, may face environmental regulations. In terms of viability, straw is easier to manage for crop-exclusive farms, particularly when produced on-site; nonetheless, its removal reduces soil organic matter and nutrients, necessitating increased fertilizer applications. While straw can be placed on the surface or incorporated into the soil, efficient decomposition typically necessitates nitrogen supplementation.

Manure works best on farms that mix crops and livestock or have easy access to local manure; however, it requires special equipment for storing, moving, and using it, and farmers must also follow certain rules. While manure significantly enhances long-term soil health, its application poses more complex management challenges. While its economic worth must offset the expenses associated with nutrient and organic matter extraction, manure offers superior nutrient enrichment and soil health benefits, albeit at a higher cost and limited availability for farms lacking animals. Straw is more readily available and simpler for grain growers to manage overall. The average cost for the custom application of liquid manure is approximately $11.65 per gallon, with standard application rates of 12,000 gallons per acre, culminating in an estimated total of $140,000 solely for application, not accounting for supplementary expenses such as storage, agitation, pumping, and transportation (https://www.agproud.com/articles/23095-how-much-does-manure-management-cost-you).

The expense of utilizing dung typically exceeds that of straw due to significant handling, shipping, and application requirements. While the transportation and application costs for solid manure approximate $3.25 per ton, its low nutritional density and weight render long-distance delivery particularly expensive. In contrast, the cost of purchased wheat straw applied at 1,000 lb per acre is estimated to be $20 per acre for materials, while total mechanical mulching expenses including labor and equipment amount to around $50 per acre. If the straw is cultivated and baled on-site, costs may decrease to about $0.50 per 50-lb bale; however, labor, baling, and spreading costs still factor into the overall total (Table 6).

Table 5. Accessibility and feasibility for straw and manure

Factor	Straw	Manure
Cost	Lower per unit, but add harvest/baling	Higher per ton, add transport/application
Accessibility	Widely available on grain farms	Limited to livestock regions
Feasibility	Simple for crop farms, may need N	Best for integrated systems, regulatory oversight

Table 6. The cost of straw and manure

Amendment	Typical Application Cost per Acre	Notes
Manure	\$140+ (liquid); \$3.25/ton (solid)	High due to transport, handling
Straw	\$20–\$50	Lower, mostly material and labor

7. CASE STUDIES AND FIELD EVIDENCE

Empirical comparisons of straw and manure in diverse agroecosystems have provided valuable insights into their distinct and combined impacts on crop yield, soil quality, nutrient cycling, and long-term sustainability. A meta-analysis across multiple agroecosystems revealed that manure application increased crop yields by 70.4%, while straw return boosted yields by 14.4% (Table 7); notably, combining straw and manure produced even higher yield improvements, highlighting a synergistic effect that surpasses the benefits of either amendment alone (Zhao et al., 2024). For example, a 9-year field experiment in Northwest China showed that returning straw with chemical fertilizer improved wheat and sunflower net incomes by 14.5% and 44.6%, respectively, while combining straw with leguminous green manure further enhanced maize yield by 19.9% and wheat yield by 10.2% compared to chemical fertilizer alone, alongside improvements in nutrient use efficiency and overall yield sustainability (Zhao et al., 2024).

In terms of soil quality and nutrient cycling, both straw and manure significantly improved soil properties, but manure exerted a stronger influence on nutrient availability and crop performance across various soil types and climatic conditions. While straw’s high humus production potential makes it particularly effective at building soil organic matter, its benefits tend to materialize more gradually and depend on proper decomposition management (Siedt et al., 2021). From a microbial and environmental perspective, both amendments enhance beneficial soil microbial communities, but manure fosters greater microbial diversity and activity, thereby accelerating nutrient cycling and carbon stabilization. In some agroecosystems, straw incorporation can temporarily reduce nutrient use efficiency due to slow decomposition, but integrating legumes or manure can counterbalance this effect, improving overall system productivity. Specifically, for maize, straw application combined with chemical fertilizer resulted in a yield sustainability index (YSI) of 0.86—higher than chemical fertilizer alone (0.83) but lower than treatments combining straw with leguminous green manure (0.91). For sunflowers, straw application alone produced the highest YSI (0.74), outperforming both chemical fertilizers alone (0.62) and the straw plus green manure combination (0.61) (Zhao et al., 2024). Studies consistently show that manure application, including cattle manure derived from straw, achieves higher and more stable crop yields compared to straw-only treatments, delivering the highest yield sustainability across most years and driving greater increases in soil organic carbon and long-term productivity.

Table 7. Effect of straw and manure on yield, soil quality and nutrient cycling

Amendment	Yield Increase	Soil Quality	Nutrient Cycling	Best Use Context
Straw	+14.4%	Gradual SOC build-up	Moderate	Where straw is abundant, for long-term soil building
Manure	+70.4%	Rapid improvement	High	Where manure is accessible, for quick fertility boost
Straw + Manure	Highest	Synergistic	Highest	Integrated systems, maximizing yield and soil health

8. FUTURE DIRECTIONS FOR RESEARCH AND POLICY

Closing significant information gaps and enhancing organic amendment strategies to maximize their agronomic, environmental, and climate benefits should be the main priorities of future research and policy orientations. A key research need is establishing long-term, field-scale studies evaluating how different organic amendments manure, straw, compost, and biochar affect soil health, carbon sequestration, microbial diversity, and crop productivity across varied climates and soil types.

Furthermore, mechanistic knowledge is vital, with an emphasis on breaking out how these changes affect soil microbial communities and nutrient cycling using modern tools like high-throughput sequencing and greenhouse gas monitoring to hone amendment choice and application rates for crops and areas (Pantelides et al., 2023). Expanding the range of amendments used has been shown to enhance soil multifunctionality and plant development, even if additional research is needed to pinpoint the best mixtures and site-specific recommendations that would guarantee maximum advantages (Lillo et al., 2025).

There is a strong need to measure how organic amendments help achieve climate-smart agriculture goals, like reducing greenhouse gas emissions, improving yield stability, saving water, and increasing resilience in areas at risk from climate change, along with other benefits. For policies and practices, we need to create specific guidelines for different regions and crops that are based on solid field data and local conditions to help effectively use organic amendments. Legislators should establish incentives, technical support, and outreach campaigns to motivate adoption, especially in areas facing severe soil degradation or climate-related stress. Moreover, adding organic materials inside circular economy models such as biogas slurry or composted municipal waste allows opportunities to close nutrient loops and support circular, sustainable agriculture. Tracking soil health, carbon storage, and environmental effects depends on robust monitoring and evaluation systems, which guarantees that adaptive management techniques may grow regularly and generate long-term sustainability benefits.

9. CONCLUSION

Closing significant information gaps and enhancing organic amendment strategies to maximize their agronomic, environmental, and climate benefits should be the main priorities of future research and policy orientations. A major research priority is to conduct long-term studies in real fields to see how different organic amendments like manure and straw impact soil health, carbon storage, microbial diversity, and crop yield in different climates and soil types. Additionally, it is important to understand how these changes impact soil microbial communities and nutrient cycling by using modern tools like high-throughput sequencing and greenhouse gas monitoring, which can help us choose the right amendments and application rates for specific crops and locations (Pantelides et al., 2023). Using a wider variety of amendments has been proven to improve soil health and plant growth, but more studies are needed to find the best combinations and specific advice for different locations to ensure the greatest benefits. There is a strong need to measure how organic amendments help achieve climate-smart agriculture goals, like reducing greenhouse gas emissions, improving yield stability, saving water, and increasing resilience in areas at risk from climate change, along with other benefits. For policies and practices, we need to create specific guidelines for different regions and crops that are based on solid field data and local conditions to help effectively use organic amendments. Legislators should establish incentives, technical support, and outreach campaigns to motivate adoption, especially in areas facing severe soil degradation or climate-related stress. Moreover, adding organic materials inside circular economy models such as biogas slurry or composted municipal waste allows opportunities to close nutrient loops and support circular, sustainable agriculture. Keeping an eye on soil health, carbon storage, and environmental impacts relies on strong monitoring and evaluation systems, ensuring that management methods can improve over time and provide lasting sustainability benefits.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

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

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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