







## REVIEW

# The Influence of Manure Application on Soil Health and Agricultural Ecosystem: A Review Focusing on China

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## ABSTRACT

Manure is essential for integrating crop and livestock systems, but intensive farming has led to a mismatch between massive manure output and its proper use. In China, about 4 billion tons are produced yearly, and raw manure application remains common, posing risks like disease transmission, root damage, soil pollution (e.g., heavy metals, antibiotics), and greenhouse gas emissions. In contrast, well-composted manure improves nutrient supply and soil health while mitigating these risks. This review systematically compares raw and composted manure, analyzing their impacts on soil, water, and air within China's policy framework (e.g., "Action Plan for Livestock Waste Utilization") and technical standards (e.g., GB/T 25246-2025). While delving into scientific evaluation methods for manure, efficient decomposition processes (including loose stacking, compact stacking, alternating loose-compact stacking, and enhancement techniques such as adding composite microbial agents and biochar), as well as safe application strategies. Key findings indicate that, compared to untreated manure, decomposed manure can increase nitrogen utilization efficiency by 47%, significantly boost soil organic matter (ranging from 122.5% to 354.8%) and humic acid content, and elevate the Shannon–Wiener diversity index of soil microbial communities to 5.6–6.0. Through the adoption of innovative processes such as the "1-Hour Nano-Composting Technology," the decomposition cycle can be substantially shortened, while effectively immobilizing or degrading emerging pollutants such as antibiotics and heavy metals. This

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### ARTICLE INFO

Received: 25 November 2025 | Revised: 26 March 2026 | Accepted: 31 March 2026 | Published Online: 6 July 2026

DOI: <https://doi.org/10.30564/re.v8i4.12818>

### CITATION

Shan, Y., Ya, R., Wu, J., et al., 2026. The Influence of Manure Application on Soil Health and Agricultural Ecosystem: A Review Focusing on China. *Research in Ecology*. 8(4): 17–27. DOI: <https://doi.org/10.30564/re.v8i4.12818>

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paper aims to provide theoretical foundations and practical guidance for promoting the safe and efficient resource utilization of manure.

**Keywords:** Uncomposted Manure; Composted Manure; Soil Environment; Safety Assessment; Compost Maturity; Resource Utilization

## 1. Introduction

As a traditional organic fertilizer, manure, rich in organic matter and essential plant nutrients, plays an irreplaceable role in improving soil structure and maintaining and enhancing soil fertility. However, with the rapid development of intensive livestock farming, a disconnect has emerged between the massive accumulation of livestock and poultry manure and its rational utilization. Notably, the direct application of uncomposted manure remains widespread. This practice stems not only from a lack of awareness among some farmers regarding the importance of composting but also leads to a series of environmental and food safety risks, including low nutrient use efficiency, greenhouse gas emissions, soil pollution, and the spread of pathogens and pests, posing potential threats to ecological environment and human health <sup>[1]</sup>.

Globally, how to effectively regulate the environmental risks of manure and promote its resource utilization has become a significant policy issue for many countries. For instance, the European Union has established a statutory ceiling on nitrogen application in farmland through a "cross-compliance" mechanism that links the Nitrates Directive with agricultural subsidies. Meanwhile, the United States enforces the Clean Water Act by mandating large-scale livestock operations to develop and implement Nutrient Management Plans under a strict zero-discharge permitting system. These international experiences demonstrate that building a policy toolkit grounded in scientific standards—one that combines regulatory constraints with economic incentives is essential to achieving sustainable manure management <sup>[2]</sup>. In China, producing approximately 4 billion tons of livestock and poultry manure annually, advancing its resource utilization is a national strategic priority. A distinct policy framework centered on "integrating crop cultivation and animal husbandry, promoting treatment through utilization" has been established. The General Office of the State Council, in its "Opinions on

Promoting the High-Quality Development of the Animal Husbandry Sector," set a mandatory target for the comprehensive utilization rate of livestock and poultry waste to exceed 80% by 2025. To this end, the Ministry of Agriculture and Rural Affairs and other departments have issued supporting policies and measures, such as "Accelerating the Treatment and Resource Utilization of Livestock and Poultry Waste," "Technical Guide for Calculating Land Carrying Capacity of Livestock and Poultry Waste," and the "Action Plan for Resource Utilization of Livestock and Poultry Waste (2017–2020)." These documents outline a general approach involving "one path, one mechanism, two priorities, and three goals," providing direction for optimizing industrial layout at the source, promoting localized and scientific land application of manure, and guiding the scientific and rational use of manure <sup>[1,3,4]</sup>.

At the technical standard and implementation level, the promulgation of national standards like the "Technical Code for Returning Livestock and Poultry Manure to the Field" (GB/T 25246-2025) explicitly requires that manure applied to land must be fully composted, providing key criteria for the harmless treatment and scientific application of manure. Practically, national-level initiatives such as pilot projects for green farming-recycling agriculture support the establishment of integrated service models covering "collection-treatment-application" and utilize information technology to establish traceable monitoring systems, providing solid guarantees for policy implementation <sup>[1,4]</sup>.

Against this policy and technical backdrop, clarifying the fundamental differences between uncomposted and composted manure is crucial. The former refers to fresh manure that has not undergone sufficient microbial fermentation, containing nutrients mostly in organic forms not readily absorbable by crops. The latter, through microbial transformation, becomes a high-quality organic fertilizer with reduced hazards. This review aims to systematically analyze the risks of uncomposted manure and the benefits of composted manure, within the context of China's pol-

icy goals, to provide a scientific basis for promoting safe resource utilization and sustainable agricultural development.

## 2. Impacts of Uncomposted Manure on the Ecosystem

### 2.1. Impacts on the Soil Ecosystem

When uncomposted manure is applied to soil, it undergoes a "secondary fermentation" process, generating substantial heat and causing a sharp increase in soil temperature. This can easily lead to "root and seedling burn," potentially causing plant death in severe cases [3]. For instance, studies show that applying fresh chicken manure can raise lettuce rhizosphere temperature by over 5 °C for several consecutive days, directly inhibiting root elongation and causing plant wilting [5]. High temperatures directly damage plant root systems, posing a more significant threat to crops at the seedling stage [1]. Furthermore, this process is often accompanied by the release of high concentrations of ammonia, which acts synergistically with the elevated temperature to exacerbate seedling injury [6].

The decomposition process of uncomposted manure consumes large amounts of oxygen in the soil, leading to temporary hypoxia, which impedes root respiration and inhibits plant growth [3]. Simultaneously, livestock manure is

often highly acidic (pH 3.6–4.7); its application to orchards can exacerbate soil acidification, leading to problems such as root rot, black roots, yellowing leaves, premature tree decline, and yellowing disease in fruit trees [7]. Uncomposted manure often contains high salt content (e.g., sodium chloride), with each cubic meter of livestock manure containing approximately 5 kg of NaCl. Crop growth is severely restricted when NaCl content exceeds 10 kg per mu [3]. Long-term salt accumulation leads to soil salinization, affecting water and nutrient uptake by crops, consequently reducing yield and quality.

Furthermore, uncomposted manure is a primary source of emerging contaminants like antibiotics and heavy metals, posing a non-negligible risk of complex pollution in soil [8,9]. Ding Dan et al. (2023) demonstrated that weakly-sorbing antibiotics (e.g., sulfadimidine and florfenicol) remaining in uncomposted manure pose a high leaching risk in soil, with a leaching potential of 37.5%–112.6%. This readily leads to groundwater contamination and exacerbates the propagation of antibiotic resistance genes (ARGs) [9]. The coexistence of heavy metals and antibiotics has the potential to form complex contaminants, modify the structure of soil microbial communities, and ultimately impair the functions of the soil ecosystem [7,8,10–14]. These diverse hazards associated with uncomposted manure are systematically categorized and summarized in **Table 1**.

**Table 1.** Primary Hazard Types of Uncomposted Manure and Their Specific Manifestations.

Hazard Aspect	Specific Manifestations	Impact Scope
Soil Hazards	Secondary fermentation causing root/scorching, soil hypoxia, exacerbated acidification, salt accumulation	Soil quality [7–11,15–19], Crop growth [9,12,14–18,20]
Water Pollution	Nutrient loss leading to eutrophication, groundwater pollution	Aquatic ecosystems [8,9]
Atmospheric Pollution	Emission of methane, ammonia, ethylene, and other harmful gases	Air quality [3], Greenhouse effect [3,10]
Biosafety	Transmission of pathogens, parasite eggs, weed seeds	Ecosystem [3,7,8,10,13,15,16,18]
Food Safety	Heavy metal accumulation, hormone residues, pathogenic microorganism contamination	Agricultural product quality [3,11,12,21], Human health [8,11,12,21]

### 2.2. Impacts on Water and Atmosphere

During natural stacking, nutrients like nitrogen, phosphorus, and potassium in uncomposted manure are easily lost due to natural decomposition, wind, and rain, with a typical utilization rate of only 50% [1,4]. These nutrients can enter rivers, lakes, and reservoirs through rainfall erosion and surface runoff, causing water eutrophication,

triggering excessive algal growth, depleting dissolved oxygen, and threatening aquatic ecosystem health [8,11].

The decomposition of uncomposted manure also produces harmful gases such as methane and ammonia, which contribute to atmospheric pollution. High concentrations of these gases can form locally in farmland, causing acid damage and root injury to soils and plants. Ethylene gas, in particular, inhibits root growth and is a primary cause of

root burn. The release of these gases not only exacerbates the greenhouse effect but also affects air quality around farmland <sup>[10]</sup>.

### 2.3. Impacts on Biosafety and Food Safety

Uncomposted manure contains large amounts of pathogenic microorganisms and parasite eggs, such as *Escherichia coli* (*E. coli*) and nematodes. Its direct application can lead to the spread of pests and diseases, posing risks to human health <sup>[1,4]</sup>. For instance, during its fermentation in soil, uncomposted chicken manure is particularly prone to breeding pathogens and fostering insect infestations. These pathogens can subsequently enter the food chain via agricultural products, triggering food safety concerns <sup>[1]</sup>.

Concurrently, heavy metals and antibiotics are widely used in feed additives <sup>[8,9,21]</sup>. The bio-availability (absorption rate) of these trace elements in animals is low, and most are excreted via manure into the environment <sup>[8,11,21]</sup>. Long-term application of manure containing high levels of heavy metals to farmland leads to soil heavy metal pollution. These elements accumulate and transform in the soil-water-plant system and ultimately pose threats to human health through the food chain <sup>[8,10,11,12]</sup>.

Furthermore, hormones present in manure also pose potential risks to food safety and the sustainable development of the agricultural industry <sup>[8,11,21]</sup>.

Studies indicate that chicken manure, due to the prevalent use of feed additives <sup>[10]</sup>, is often a significant source of antibiotics and heavy metals <sup>[8,11,12]</sup>. Pig manure also tends to have high salt and heavy metal content <sup>[9,10,12,13]</sup>. These pollutants migrate and accumulate in the soil-crop system, eventually threatening human health through the food chain <sup>[11,12]</sup>.

## 3. Advantages and Mechanisms of Composted Manure

### 3.1. Nutrient Availability and Environmental Friendliness

Under the action of microbial fermentation, the composting process not only converts organic nutrients into inorganic, readily available forms for crops but also effectively degrades residual organic pollutants like antibiotics in manure <sup>[20-22]</sup>. Wang Bing et al. (2025) confirmed that adding composite composting microbial agents significant-

ly optimizes the microbial community structure during fermentation, promotes the proliferation of functional strains such as *Methylobacillus* and *Rhodobacter sphaeroides*, accelerates organic matter transformation, and improves compost quality <sup>[14]</sup>. Dong Weiwei et al. (2023) confirmed that Comparing to inoculant-free controls, inoculant application accelerated the compost's thermophilic stage (8 vs. 15 days), and significantly increased compost total N contents (+47%) and N-reductase activities (nitrate reductase: +60%; nitrite reductase: +219%) <sup>[23]</sup>.

Composted manure is rich in beneficial microorganisms and enzymes. These microorganisms and enzymes facilitate the conversion of organic nitrogen and phosphorus into inorganic forms for direct plant uptake <sup>[15,20]</sup>. Simultaneously, they form stable complexes with elements like calcium, magnesium, iron, and aluminum in the soil, reducing phosphorus fixation and increasing soil available phosphorus content and phosphorus fertilizer utilization efficiency <sup>[10,15,16,20]</sup>. The Bio-nanomembrane Composting Process can increase the content of humic acid, nitrogen, phosphorus, and other elements in the final compost product by over 30% compared to traditional fermentation methods <sup>[24,25]</sup>. Donghua University (2023) indicated that through the introduction of *Bacillus velezensis* SQR9 for composting treatment, the dissolved organic carbon content increased by 18.9 times, and the humic acid content increased by 3.7 times. These changes significantly enhanced nutrient availability <sup>[26]</sup>.

Regarding environmental friendliness, the heat generated during the composting process (temperatures can reach 60–70 °C) effectively kills most harmful eggs, weed seeds, and pathogens, significantly reducing the risk of disease and pest transmission <sup>[20,27]</sup>. Moreover, fully composted manure does not undergo secondary fermentation after soil application, avoiding the production of harmful gases and soil hypoxia, thereby reducing atmospheric pollution and potential harm to crops <sup>[13,28]</sup>.

### 3.2. Soil Improvement and Ecosystem Services

The humic colloids present in composted manure promote the formation of soil aggregate structure, making the soil looser, improving soil water and air conditions, benefiting root growth, and enhancing crop stress resistance <sup>[16,17,20,29]</sup>. This aggregate structure significantly reduces soil bulk density, improves soil permeability, mitigates

the water-air contradiction, and creates a more suitable soil environment for crop growth <sup>[20,29]</sup>.

Composted manure enhances the soil's water and nutrient retention capacity, increases soil temperature, and promotes the activity and reproduction of beneficial soil microorganisms <sup>[16,17,20]</sup>. These effects not only improve soil fertility but also enhance the resilience of agricultural ecosystems, providing stable growth conditions for crops <sup>[17,20,22]</sup>.

Furthermore, composted manure serves not only as a nutrient source but also as a natural "soil temperature regulator." Based on their properties, manures are categorized as hot, warm, or cool, related to the heat generated during decomposition (fermentation heat) and the ability of organic matter to improve soil physical properties <sup>[1]</sup>. In practice, selecting and using them according to local and seasonal conditions can effectively create a suitable rhizosphere environment for crops, buffering against adverse effects from drastic temperature fluctuations. The agricultural saying "In winter, sheep and horse manure are like quilts; in summer, cattle manure is like a cooling mat" vividly reflects this ecological phenomenon. Hot manures (e.g., sheep, horse, rabbit manure), high in cellulose and loose in texture, continue to decompose slowly in soil, releasing heat and raising soil temperature, beneficial for overwintering and early spring crops. Cool manures (e.g., cattle manure), rich in organic matter, improve soil structure and enhance water retention; water evaporation carries away some heat, providing a cooling effect, suitable for summer and shade-tolerant crops. Warm manures (e.g., pig manure) help balance soil temperature and are widely applicable, robust choices. Long-term Research results indicate that

compared to uncomposted manure, composted manure has a more pronounced effect on improving the soil micro-ecosystem <sup>[20,22,28,29]</sup>. Through an 11-year continuous experiment, Chen et al. (2019) found that long-term application of composted chicken manure significantly enhanced the richness and diversity of soil microbial communities, enriching beneficial microbial phyla such as Proteobacteria and Gemmatimonadetes, which play key roles in soil nutrient cycling <sup>[13,18,20,22,28]</sup>.

### 3.3. Scientific Indicators for Compost Maturity

During composting, except for dairy cattle manure, the total nitrogen content in other livestock manures generally decreases initially and then stabilizes <sup>[13,21]</sup>. The decrease in ammonium nitrogen content and the increase in nitrate nitrogen content are important indicators of the composting process (e.g., the ratio of alkali-hydrolyzable nitrogen to total nitrogen, and the ratio of ammonium nitrogen to total nitrogen) <sup>[13,21]</sup>.

Comparative studies on long-term application of fresh versus composted livestock manure show that composted manure better enhances the humification degree of soil dissolved organic matter (DOM). Soil available nutrients and DOM humification components are the main factors influencing soil microbial community structure <sup>[13,18,20]</sup>. Chen Jing et al. (2019) found that soils treated with composted chicken manure had higher microbial community richness and diversity, showing clear advantages in enhancing the  $\alpha$ -diversity of microbial communities <sup>[13]</sup>. The main advantages of composted manure and their underlying mechanisms are systematically summarized in **Table 2**.

**Table 2.** Main Advantages of Composted Manure and Their Mechanisms of Action.

Advantage Category	Specific Manifestations	Mechanism of Action	Evidence from Studies
Fertilizer Efficiency and Soil Improvement	Improves soil structure and enhances soil organic matter and nutrient content.	The long-term application of composted manure facilitates the continuous input of stable organic matter and mineral nutrients into the soil, a process mediated by soil microbial activity <sup>[13]</sup> .	The results of an 11-year long-term field experiment showed that the application of composted manure increased soil organic matter by 122.5% to 354.8%, and significantly enhanced the content of nitrogen and phosphorus in the soil <sup>[13]</sup> .
	Promotes the humification of soil organic matter and enhances soil water and nutrient retention capacity.	The humic substances generated during composting contribute to an increased humification degree of the dissolved organic matter in soil <sup>[13]</sup> .	Soil treated with composted manure exhibited a 40.3% to 43.3% higher humification index compared to the control group, along with a richer content of humic-like substances <sup>[13]</sup> .
	Improves the structure of the soil microbial community and enhances the proliferation of beneficial microorganisms, soil enzyme activity, and crop stress resistance.	Providing a balanced C/N ratio and enriching beneficial microbiota to enhance community diversity and activity <sup>[13]</sup> .	Under the application of composted chicken manure, the soil exhibited the highest Shannon-Wiener diversity index (5.6–6.0), along with a greater abundance of Proteobacteria (a copiotrophic microbial group) <sup>[13]</sup> .

Table 2. Cont.

Advantage Category	Specific Manifestations	Mechanism of Action	Evidence from Studies
Production and Process Efficiency	Significantly shortens the composting cycle of manure.	Rapid initiation and completion of thermophilic fermentation via inoculants or innovative processes <sup>[30-33]</sup> .	The addition of a composting agent can extend the duration of temperatures above 50 °C from 12 days to 26 days, thereby accelerating the maturation process <sup>[13]</sup> . The "1-Hour Nano-Composting Technology" reduces the composting cycle from 30 days to 1 hour, achieving a 720-fold increase in efficiency <sup>[33]</sup> .
	Enhances the stability and efficiency of the composting process.	The efficient degradation of organic matter and heat generation are achieved through the inoculation of specific functional microbes (e.g., <i>Aspergillus niger</i> , <i>Bacillus subtilis</i> ) during the composting stage <sup>[31]</sup> .	Inoculation with a composting agent elevates the temperature during the thermophilic phase of composting by 7–10 °C and enables sustained substrate degradation through core CAZymes (Carbohydrate-Active Enzymes) <sup>[31]</sup> .
Environment and Safety	Effectively eliminates or passivates harmful substances.	The thermophilic phase eliminates pathogens, while the composting process, often augmented with specific additives, allows for the passivation of heavy metals and degradation of antibiotics and hormones <sup>[13,33,34]</sup> .	The addition of biochar and other amendments can passivate heavy metals through mechanisms such as adsorption and precipitation <sup>[34]</sup> . The 1-Hour Nano-Composting Technology achieves 100% harmless treatment, effectively eliminating harmful substances including bacteria, hormones, antibiotics, and heavy metals <sup>[33]</sup> .
	Reduces greenhouse gas emissions and environmental pollution.	Waste valorization with reduced GHG emissions through rapid aerobic fermentation <sup>[32,33]</sup> .	The "1-Hour Nano-Composting Technology" reduces carbon emissions by over 30% compared to traditional composting methods, enabling the genuine resolution of manure pollution at its source <sup>[33]</sup> .

## 4. Production and Scientific Application Strategies for Composted Manure in Practice

### 4.1. Manure Composting Methods and Techniques

Manure composting methods include loose stacking, compact stacking, and loose-compact alternating stacking<sup>[13]</sup>. Loose stacking involves piling fresh manure loosely on a composting site, maintaining good aeration for rapid decomposition under high-temperature conditions. This method suits urgent fertilizer needs but results in relatively lower nitrogen losses (The nitrogen loss rate is greater than 30%). Compact stacking involves removing manure from livestock pens and stacking it layer by layer on the composting site, compacting it. The pile height should be 1.5–2 m, sealed with soil after stacking. This method promotes greater humus accumulation while resulting in higher nitrogen loss, with the nitrogen loss rate reaching 57%–63%, but has a relatively longer composting cycle, typically reaching semi-maturity after 3–4 months and full maturity only after six months<sup>[35]</sup>. The loose-compact alternating method combines the advantages of both. Fresh manure is first loosely piled about 1 m high, not compacted, allowing natural fermentation. After 2–3 days, the internal tempera-

ture can reach 60–70 °C. Then, fresh manure continues to be added layer by layer until the height reaches 2–2.5 m, finally sealed with soil. This method achieves semi-maturity in 1.5–2 months and full maturity in 4 months, balancing efficiency and quality. To improve organic fertilizer efficiency and reduce nitrogen loss (The nitrogen loss rate is approximately 41%), 4% super-phosphate can be added and mixed during stacking<sup>[13]</sup>. In recent composting practices, inoculating composite microbial agents is one of the most efficient means to enhance composting efficiency and quality. The composting agent developed by Chen et al. (2019) (including *Saccharomyces cerevisiae*, *Methylobacillus*, etc.) increased the organic matter content of the composted fertilizer to over 56%, total nitrogen to greater than 5%, and produced an acidic fertilizer (pH 4.78–5.90), more conducive to ameliorating alkaline soils<sup>[13]</sup>. According to information from Donghua University, the "1-Hour Composting Technology for Organic Solid Waste" developed by Professor Cai Dongqing's team achieves a break through improvement in the treatment efficiency of organic waste. This technology significantly shortens the composting cycle from the traditional 30 days to just 1 h, representing a 720-fold increase in efficiency, and accomplishes 100% harmless treatment of the waste by effectively eliminating bacteria, residual hormones, antibiotics, and heavy metals. The organic fertilizer produced by this technology

demonstrates superior quality: its fulvic acid content reaches 3%–6% (compared to only about 1% in traditional organic fertilizers), and field applications have shown yield increase effects of 15%–50%. All product indicators fully comply with the requirements of the Chinese industry standard NY525-2021 for organic fertilizers. Furthermore, this technology offers significant economic and environmental benefits. It can save approximately 70% in space and labor cost and helps reduce carbon emissions by over 30%, providing an innovative solution for the resource-efficient and high-performance utilization of organic solid waste <sup>[33]</sup>.

#### 4.2. Efficient Application Techniques for Composted Manure

Firstly, deep plowing is necessary after manure application. If large amounts of manure are concentrated in the top 10–15 cm of soil (about 25% moisture content, 24–36 t ha<sup>-1</sup>), even if composted, it can affect root growth when application rates are high and tillage is shallow. Therefore, after application, deep plowing to over 30 cm is required to ensure thorough mixing of manure and soil <sup>[1,4]</sup>.

Secondly, sandy soils with poor moisture and nutrient retention should be amended with pure chicken or pig manure. These manures have relatively high purity and nutrient content, and their viscous nature is beneficial for improving sandy soils <sup>[13,20]</sup>. Clayey soils should receive manures high in organic matter but low in mineral elements, such as sheep or cattle manure, or chicken/pig manure containing sand, rice husks, or straw. This improves the physical properties of clay soil and enhances its permeability <sup>[20]</sup>.

Furthermore, composted manure should be used in combination with chemical fertilizers and bio-bacterial fertilizers. Although the nutrients in manure are comprehensive, their total amount often does not meet crop demand. Combined use with chemical fertilizers can reduce the adverse effects of chemical fertilizer residues on soil while ensuring timely nutrient supply for crop growth <sup>[17,19,20]</sup>. Combined use accelerates manure decomposition, enhances soil improvement effects, promotes the reproduction of microbial communities via substances in the manure, facilitates the rapid formation of soil aggregates, and consolidates the protective and growth-promoting effects of beneficial microbiota on plant roots <sup>[13,14,17,20,22,28,29]</sup>.

## 5. Research Prospects

In recent years, research on manure has exhibited a distinct trend toward interdisciplinary integration. It is advancing through the convergence of microbiology, environmental science, agronomy, engineering, and management, which is progressively driving collaborative innovation and profound development in this field.

### 5.1. Mechanism Exploration and In-Depth Analysis

- (1) **Soil Microbial Driving Roles:** Focus on elucidating the processes by which different manures regulate specific soil microbial communities (e.g., composition and diversity of bacteria, fungi) and analyze the role of these microorganisms in driving key processes, notably organic carbon transformation and humus formation. Recent studies found that manure can increase the temperature sensitivity of soil organic carbon by significantly increasing soil  $\alpha$ -Proteobacteria <sup>[13,22]</sup>. This research falls within the domain of applied basic research and represents a key focus from the perspective of manure composting microbiology.
- (2) **Organic Matter Components and Characteristics:** Investigate the impact of long-term application of composted versus uncomposted manure on the composition and structure of soil dissolved organic matter (DOM). Enhancing the degree of humification is crucial for soil fertility and carbon sequestration.
- (3) **Nutrient Cycling and Greenhouse Gas Emissions:** Uncover the unique role of manure in the transformation processes of soil nutrients like nitrogen and phosphorus, particularly the pathways influencing nitrous oxide (N<sub>2</sub>O) emissions. Recent research showed that under conditions of sufficient phosphorus, manure replacing chemical fertilizer can effectively reduce N<sub>2</sub>O emissions, highlighting the importance of balanced nutrient management <sup>[30]</sup>.

### 5.2. Technological Innovation and Process Enhancement

Future technological development should focus on optimizing the composting process and its integration into

farming systems.

- (1) Mechanism of the Composting Process: Research should focus on the targeted regulation of composting using compound microbial inoculants (e.g., *Sphingobacterium*, *Paenibacillus*) to accelerate humus formation, shorten processing time, and improve product quality.
- (2) Development and Application of Novel Additives: Explore adding materials like biochar during composting to improve pile porosity, adsorb harmful gases and heavy metals, and produce high-quality biochar-based organic fertilizer through co-fermentation with manure, achieving "efficient, clean, and high-value" manure utilization.
- (3) Equipment and Process Optimization: Design and optimize specialized stirring mechanisms, insulation techniques, etc., for manure treatment challenges in different climatic regions (e.g., cold regions like Northeast China), enhancing the efficiency and stability of the entire aerobic composting system.

### 5.3. Environmental Risk and Precise Control

- (1) Greenhouse Gas Emission Reduction: Focus on how to maximize manure fertilizer efficiency while minimizing greenhouse gas emissions through nutrient allocation ratios (e.g., nitrogen-phosphorus synergy), management practices, and technological innovations.
- (2) Control of Emerging Pollutants: Continuously monitor and evaluate the migration and accumulation patterns of antibiotics, antibiotic resistance genes (ARGs), and heavy metals in the soil-crop system during manure application, and identify driving factors. Establish models predicting antibiotic leaching potential based on adsorption constants<sup>[9]</sup>, and develop effective interception and control technologies to provide scientific tools for groundwater pollution risk assessment.
- (3) Precision Nutrient Management: Establishing more refined application thresholds and technical guidelines for manure land application based on soil carrying capacity and crop nutrient demand is essential. This requires integrating soil testing, manure charac-

terization, and crop models to develop site-specific recommendations.

- (4) Integration and Promotion of Technical Models: Tailored to the characteristics of different regions, promote efficient and simplified technical models like "manure + mechanical deep application" and "manure + integrated water-fertilizer system." Establish core demonstration zones to drive wider adoption, gradually promoting the safe and efficient use of manure.

## 6. Conclusion

The transition from uncomposted to composted manure application is not merely an agronomic improvement but a necessary step for sustainable agriculture, especially in regions like China with intensive livestock production. Composting transforms manure from a potential pollutant into a valuable resource that enhances soil health, mitigates environmental risks, and aligns with national policy goals for waste utilization. Future success depends on interdisciplinary research, technological innovation in composting processes, and the effective integration of scientific knowledge into practical, region-specific application strategies and supportive policies.

## Funding

This work was supported by the Sustainable Development Program for Ecological Grassland Industry (2023CYZX03); Inner Mongolia Autonomous Region Key R & D and Achievement Transformation Program (2025YFDZ0082); Inner Mongolia Autonomous Region Academician and Expert Workstation Establishment Project; Inner Mongolia Autonomous Region Innovation Startup Support Plan for Returned Overseas Scholars; Inner Mongolia Autonomous Region-level Scientific Research Project (NMLCZ-2023-001).

## Institutional Review Board Statement

Not applicable.

## Informed Consent Statement

Not applicable.

## Data Availability Statement

This article is a review and does not contain original research data. All data cited are from previously published sources, which are appropriately referenced in the manuscript.

## Acknowledgments

The authors would like to thank all individuals and institutions who contributed to the successful completion of this study.

## Conflicts of Interest

The authors declare no conflict of interest.

## AI Use Statement

During the preparation of this work, the authors used DouBao/DeepSeek for language polishing and copyediting. The authors subsequently reviewed and edited the content as necessary and take full responsibility for the final content of the published article.

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