

Review

Multi-Scale Control Strategies for Nitrogen Loss During Aerobic Composting of Agricultural Waste: A Review

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Abstract

Aerobic composting is an important pathway for the resource utilization of agricultural waste. However, nitrogen loss during composting not only reduces the nutrient value of the final product but also causes environmental burdens, particularly through ammonia (NH₃) volatilization and nitrous oxide (N₂O) emissions. The objective of this review is to systematically summarize the sources, pathways, and mechanisms of nitrogen loss during aerobic composting of agricultural waste and to evaluate multi-scale control strategies for enhancing nitrogen retention and mitigating environmental emissions. This review addresses an important gap by integrating the sources, pathways, and mechanisms of nitrogen loss with practical mitigation strategies across the feedstock, in-process, post-treatment, system design, and macro scales. The synthesis indicates that the major nitrogen loss routes during aerobic composting include NH₃ volatilization, N₂O emissions, and nitrate leaching. From a multiscale perspective, the review synthesizes control strategies spanning feedstock pretreatment, including optimization of carbon-to-nitrogen (C/N) ratio, adsorbent amendment, and microbial inoculation; in-process regulation, including aeration, moisture, temperature, pH; and post-treatment approaches for nitrogen stabilization and resource recovery. The supporting roles of reactor innovation, intelligent process control, and policy and regulatory measures are also discussed. Finally, current bottlenecks and future research directions are summarized from environmental and economic perspectives, with particular emphasis on interdisciplinary integration and technological innovation to enhance nitrogen retention during composting.

Keywords: ammonia volatilization; nitrogen retention; nitrous oxide emissions



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1. Introduction

Agricultural production generates enormous quantities of organic residues, including livestock manure, crop straw, and by-products from food processing. Recent estimates indicate that annual global agricultural waste production is projected to reach 2.6 billion tons by 2030 [1]. If these materials are not managed properly, they can occupy land, contaminate soil and water, and intensify greenhouse gas emissions. Aerobic composting converts such residues into a more stable humified product through microbial degradation and remains one of the most widely adopted biological treatment options because it combines waste reduction with resource recovery [2]. Compared with landfilling or incineration, compost-

ing is better aligned with circular agriculture, but its performance is often constrained by substantial nitrogen loss [3].

Nitrogen is a key determinant of compost quality because both the amount and the form of nitrogen retained at the end of composting directly affect the fertilizer value of the product. During aerobic composting, however, nitrogen is frequently lost through gaseous and liquid pathways, with recent studies indicating that nitrogen loss during high-temperature composting can reach 40–70% of the initial nitrogen, and even higher losses under poorly controlled conditions [4]. Nitrogen loss is largely governed by the balance among ammonification, nitrification, and denitrification. These processes determine whether organic nitrogen is mineralized to $\text{NH}_4^+\text{-N}$, retained through microbial assimilation and humification, oxidized to $\text{NO}_3^-\text{-N}$, or lost through NH_3 volatilization, N_2O emissions, and nitrate leaching. NH_3 volatilization is usually the dominant pathway [5], and once emitted, NH_3 contributes to secondary particulate formation, air-quality deterioration, and acid deposition [6]. N_2O emissions are also important because N_2O has a 100-year global warming potential 273 times that of CO_2 , thereby representing a major source of greenhouse gas emissions from composting systems [7]. Nitrate-rich leachate can contaminate surface water and groundwater, increasing the risk of eutrophication and drinking-water quality deterioration [8].

Reducing nitrogen loss therefore matters at several levels. From an agronomic standpoint, higher nitrogen retention increases the fertilizer value of compost and can help reduce dependence on synthetic fertilizers. From an environmental standpoint, suppressing NH_3 , N_2O , and nitrate losses lowers the atmospheric and aquatic burdens associated with composting. Economically, better nitrogen conservation improves product quality and can raise the market value of compost. Previous studies and reviews have provided valuable insights into nitrogen transformation, NH_3 volatilization, N_2O emissions, composting additives, microbial regulation, aeration optimization, and reactor-based emission control during aerobic composting [9,10]. However, many of these studies have primarily focused on individual nitrogen-loss pathways or specific mitigation measures, whereas the interactions among feedstock properties, microbial nitrogen conversion, process parameters, post-treatment stabilization, reactor configuration, and management or policy incentives have not been fully integrated. Moreover, recent advances over the last few years have shifted the field from conventional emission reduction toward coordinated nitrogen-retention and nutrient-recovery strategies, including functional additives, microbial inoculation, membrane-covered and in-vessel composting systems, ammonia capture, condensate recirculation, and intelligent process monitoring. These developments indicate that nitrogen retention during composting should be understood not only as a biochemical process governed by microbial nitrogen transformation, but also as an engineering and management challenge requiring multiscale regulation from feedstock pretreatment and process control to reactor design and macro-scale policy support.

The objective of this review is to critically synthesize the sources, pathways, and mechanisms of nitrogen loss during aerobic composting of agricultural waste and to evaluate control strategies for enhancing nitrogen retention and mitigating environmental emissions. In this review, “multiscale” refers to five interconnected intervention scales for nitrogen-loss control: feedstock pretreatment, process regulation, post-treatment management, reactor design, and policy/regulatory support. These scales are discussed on the basis of microbial nitrogen transformation and humification chemistry, which provide the mechanistic foundation for nitrogen retention. Specifically, this review first analyzes how feedstock characteristics and composting conditions influence nitrogen transformation and loss, and then organizes nitrogen-retention strategies according to key intervention points before, during, and after composting, as well as at the engineering-system and governance levels.

It also compares the environmental and engineering implications of these strategies and identifies the main bottlenecks limiting their broader application.

2. Sources and Mechanisms of Nitrogen Loss During Aerobic Composting

2.1. Feedstock Composition and Its Relationship with Nitrogen Loss

Agricultural wastes such as manure, straw, rice husks, and food-processing residues differ markedly in nitrogen form, carbon quality, moisture, buffering capacity, and structure, and these differences largely determine how much nitrogen is lost during composting. Manure typically contains high concentrations of total nitrogen, a large share of which is present as readily mineralizable compounds or $\text{NH}_4^+\text{-N}$, but it often has a relatively low carbon-to-nitrogen (C/N) ratio and limited structural carbon. Under these conditions, ammonification can outpace microbial assimilation, leading to $\text{NH}_4^+\text{-N}$ accumulation and substantial NH_3 volatilization, especially when temperature exceeds 50°C and pH shifts into the alkaline range [11,12]. Crop straw shows the opposite pattern: it is rich in carbon but poor in nitrogen. Straw-rich composting mixtures therefore tend to have a high C/N ratio, which may reduce early nitrogen loss but can also impose nitrogen limitation on microbial activity, resulting in slower temperature rise, weaker mineralization, and delayed humification [13].

The initial speciation and bioavailability of nitrogen strongly influence its transformation pathway during composting. Fresh livestock manure often contains urea, uric acid, and other labile nitrogenous compounds that are rapidly hydrolyzed and can cause an early surge in $\text{NH}_4^+\text{-N}$ concentration, creating a pronounced risk of ammonia loss during the initial thermophilic stage [14]. By contrast, nitrogen bound in proteins, peptides, or more complex organic matrices are released more gradually, giving microbial assimilation more time to compete with ammonification. A further fraction of nitrogen is embedded in lignified or heterocyclic structures with low bioavailability; this pool contributes little to short-term loss but becomes an important precursor of stable humified nitrogen in the final compost [15].

Carbon availability governs the capacity of microorganisms to immobilize mineral nitrogen [16]. Readily degradable carbon sources such as soluble sugars, starch, and part of the hemicellulose fraction can rapidly fuel microbial growth and thereby stimulate nitrogen assimilation during the early phase of composting [17]. Cellulose decomposes more slowly and can sustain nitrogen immobilization later in the process, whereas lignin is highly recalcitrant but still matters because it can physically protect organic nitrogen from rapid breakdown and provides structural precursors for humus formation [18,19]. This is why feedstocks with balanced carbon quality often retain nitrogen more effectively than materials dominated by either highly labile nitrogen or highly recalcitrant carbon alone.

Physical structure and buffering properties also affect nitrogen loss. Bulking materials such as straw or coarse plant residues increase pile porosity, improve oxygen diffusion, and reduce the likelihood of anaerobic pockets that favor denitrification [20]. At the same time, many manures contain carbonates and organic acid salts that buffer the composting matrix toward alkaline conditions, often keeping pH between 8.0 and 9.0, which substantially increases the potential for NH_3 volatilization [21,22].

To facilitate comparison among common agricultural residues, representative physico-chemical characteristics related to nitrogen loss potential are summarized in Table 1. The main challenge differs among raw materials: nitrogen-rich and high-moisture manures, such as swine manure, require control of rapid $\text{NH}_4^+\text{-N}$ accumulation, NH_3 volatilization, and anaerobic N_2O formation, whereas straw-rich mixtures require improved degradability, balanced nitrogen availability, and enhanced humification. This feedstock-dependent behavior indicates that nitrogen-retention strategies should be selected according to the

initial nitrogen form, C/N ratio, moisture content, porosity, buffering capacity, and carbon degradability of the raw materials.

Table 1. Representative properties of common agricultural residues used in aerobic composting.

Feedstock/Residue	Typical Role in Composting	C/N Ratio	Key Contents/ Characteristics	Implications for Nitrogen Loss	Ref.
Chicken manure/chicken litter	N-rich main substrate	<10 to <20	High N availability; chicken manure may contain 3–8% N	High risk of early NH_4^+ -N accumulation and NH_3 volatilization, especially under high temperature and alkaline pH	[11,14]
Pig manure	N-rich main substrate	Usually low to moderate	Rich in readily mineralizable N and moisture	High NH_3 loss potential if C availability and porosity are insufficient	[21,22]
Wheat straw	Carbonaceous bulking agent	High C/N, 89.84–92.15 reported	Low moisture; rich in cellulose, hemicellulose, and lignin	Improves porosity and C supply, but excessive addition may slow decomposition	[13,18,20]
Rice husk	Structural bulking agent	High C/N, commonly >50	Rich in cellulose, lignin, and ash/silica	Improves aeration and structure but decomposes slowly; useful for reducing anaerobic microsites	[13]
RS, SS, WS, TS, CS, CP	C-rich main substrate	High C/N, 31.1–77.5 reported	Rich in cellulose, lignin	carbon bioavailability modulates nitrogen retention	[16]
Food-processing residues/food waste	Labile C and N source	Generally low C/N	High moisture, low porosity, and abundant easily degradable carbohydrates, proteins, and lipids	Rapid degradation can intensify acidification, oxygen depletion, and N loss unless bulking agents are added	[17]

Note: RS, rapeseed straw; SS, soybean straw; WS, wheat straw; TS, tomato stalk; CS, chili stalk; CP, cassava plant residue.

2.2. Nitrogen Transformation Pathways and Loss Routes

Nitrogen transformation during aerobic composting involves four closely linked processes: ammonification, microbial immobilization, nitrification, and humification [21,23]. Ammonification dominates early, when proteins, urea, and other organic nitrogen compounds are decomposed into NH_4^+ -N. For example, urea can be hydrolyzed according to the simplified pathway: $\text{CO}(\text{NH}_2)_2 + 2\text{H}_2\text{O} \rightarrow 2\text{NH}_4^+ + \text{CO}_3^{2-}$. Similarly, protein- and amino acid-derived organic nitrogen can be mineralized to NH_4^+ -N through microbial degradation. This early mineralization is mainly driven by heterotrophic ammonifiers and ureolytic microorganisms, including many members of *Firmicutes*, *Proteobacteria*, and related bacterial groups. During the thermophilic phase, thermotolerant heterotrophs, particularly *Bacillaceae* and other *Firmicutes*, often become important contributors to organic matter degradation, ammonification, and heat generation. Part of the resulting mineral

nitrogen is then assimilated by microorganisms and incorporated into biomass, a step that is essential for nitrogen retention and strongly dependent on carbon supply.

As the pile cools and oxygen becomes more available, nitrification converts $\text{NH}_4^+\text{-N}$ to $\text{NO}_2^-\text{-N}$ and then to $\text{NO}_3^-\text{-N}$ through two main steps: $\text{NH}_4^+ + 1.5\text{O}_2 \rightarrow \text{NO}_2^- + 2\text{H}^+ + \text{H}_2\text{O}$, followed by $\text{NO}_2^- + 0.5\text{O}_2 \rightarrow \text{NO}_3^-$. This process is mediated mainly by ammonia-oxidizing bacteria and archaea (AOB and AOA), such as *Nitrosomonas*-, *Nitrospira*-, and *Nitrososphaera*-like groups, and by nitrite-oxidizing bacteria (NOB), such as *Nitrobacter*- and *Nitrospira*-like groups. In general, nitrifying microorganisms are more active during the cooling and maturation phases, when temperature declines and oxygen penetration improves, although thermotolerant nitrifiers may also contribute under suitable thermophilic microenvironments. In later stages, humification stabilizes part of the retained nitrogen through association with humic substances, creating a more persistent organic nitrogen pool in the mature compost. This process is closely associated with lignocellulose-degrading and humus-forming microorganisms, including *Actinobacteria*, fungi, and thermotolerant bacterial groups. Mechanistically, reactive oxygen species (ROS)-mediated lignin oxidation generates phenolic and quinone-like intermediates that react with $\text{NH}_4^+\text{-N}$ and organic N compounds to form N-containing aromatic structures and humic-bound complexes, thereby stabilizing labile nitrogen and reducing its loss through volatilization, denitrification, and leaching [19].

These nitrogen transformations are regulated by microbial functional genes involved in ammonification, nitrification, and denitrification, such as *ureC* for urea hydrolysis, *amoA* for ammonia oxidation, *nirS*/*nirK* for nitrite reduction, and *nosZ* for N_2O reduction [23]. Changes in the abundance or activity of these functional genes help explain stage-dependent $\text{NH}_4^+\text{-N}$ conversion, $\text{NO}_3^-\text{-N}$ accumulation, and N_2O formation, thereby linking microbial mechanisms with process-scale controls such as oxygen availability, moisture, temperature, and pH. Together, these pathways determine the balance between nitrogen mineralization, retention, stabilization, and potential loss during aerobic composting.

Nitrogen is lost mainly through gaseous and liquid pathways (Figure 1). Among these, NH_3 volatilization is usually dominant, accounting for 79–94% of total nitrogen loss and representing 9.6–46% of the initial total nitrogen in many composting systems [11,24,25]. This pathway is particularly important during the early and thermophilic stages, when rapid mineralization generates large amounts of $\text{NH}_4^+\text{-N}$ and high temperature and pH favor conversion to NH_3 . Denitrification is generally the second major pathway and can account for 0.2–9.9% of total loss, corresponding to 0.1–5% of the initial total nitrogen [24,26]. It occurs when localized oxygen limitation allows $\text{NO}_3^-\text{-N}$ to be reduced to N_2O and N_2 . In addition to classical denitrification, anaerobic ammonium oxidation (anammox) may also occur in oxygen-limited microsites of composting piles, where $\text{NH}_4^+\text{-N}$ and $\text{NO}_2^-\text{-N}$ are converted to N_2 , representing a potential but often overlooked nitrogen-loss pathway [27]. Leaching is usually less important in well-managed systems and often contributes less than 2% of the initial total nitrogen, but losses can increase sharply in uncovered windrows or under rainfall exposure because $\text{NO}_3^-\text{-N}$ is highly mobile in the liquid phase [28].

2.3. Factors Governing Nitrogen Loss

Nitrogen loss is regulated by several interacting factors, among which the initial C/N ratio is fundamental [29]. When the C/N ratio is too low, typically below about 20, nitrogen is supplied more rapidly than microorganisms can assimilate it, leading to $\text{NH}_4^+\text{-N}$ accumulation and severe NH_3 volatilization [30]. When the C/N ratio is too high, often above 35, nitrogen becomes limiting for microbial growth, organic matter degradation slows, and the overall composting period is prolonged [31,32]. For many substrates, a C/N ratio in the range of 25–30 is considered a practical benchmark [21,30], but the actual

optimum is feedstock-dependent. A recent meta-analysis suggested a lower optimum range (20–25) for swine and poultry manure and a somewhat higher range (25–35) for cattle and sheep manure [33].

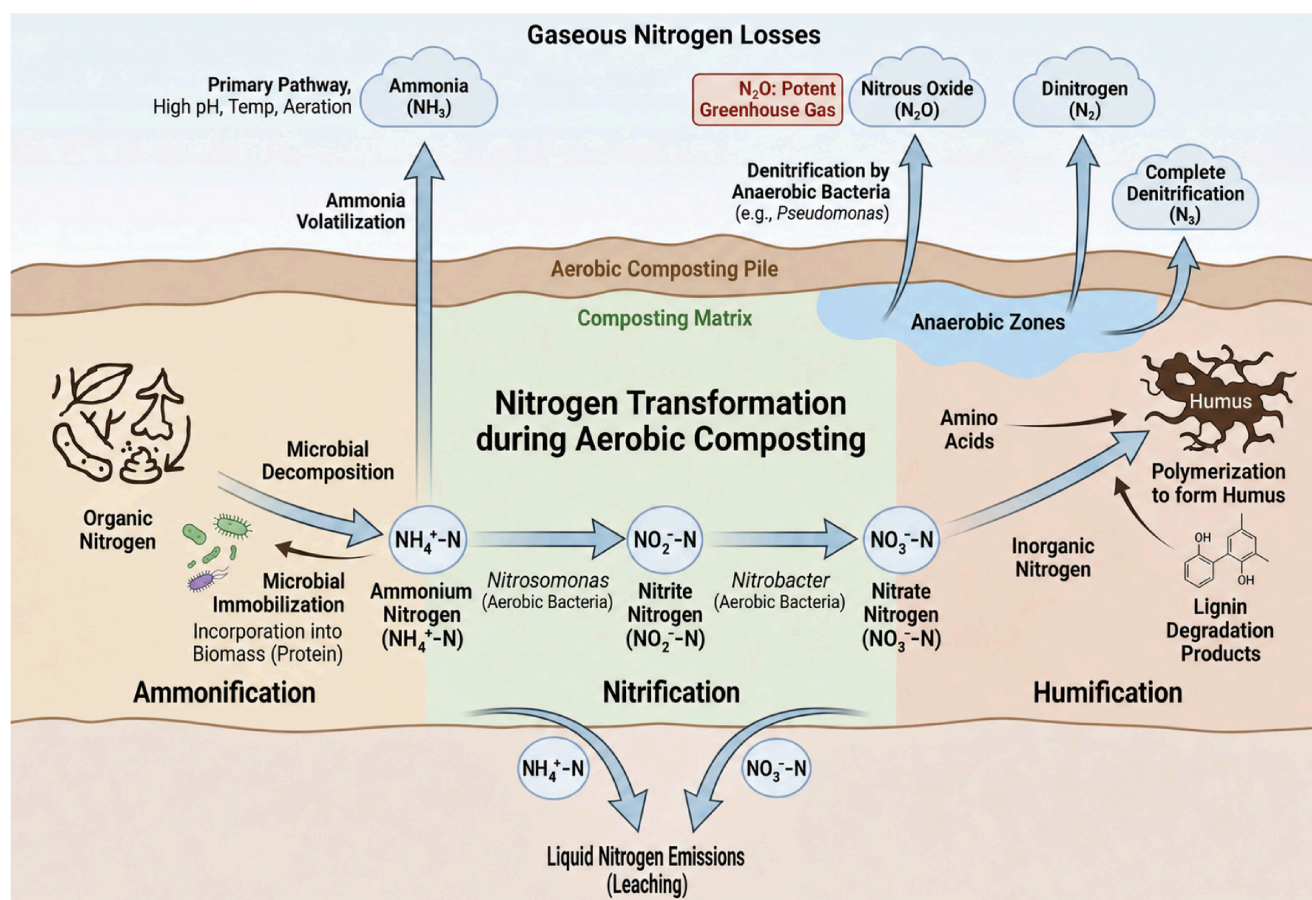


Figure 1. Schematic diagram of the primary nitrogen transformation pathways and major loss routes (NH_3 volatilization, N_2O emission, and $\text{NO}_3^-\text{-N}$ leaching) during aerobic composting of agricultural waste.

Moisture content regulates both microbial physiology and oxygen transport [34,35]. At adequate 60–65% moisture, microbial metabolism is generally well supported. If moisture rises above this range, pore spaces fill with water, oxygen diffusion is restricted, and anaerobic microsites can form, which promotes denitrification and the release of N_2O and N_2 [36]. If moisture falls too low, microbial activity is suppressed by water limitation and the conversion of organic matter and nitrogen slows markedly [37].

Temperature, pH, and aeration interact strongly during composting and largely determine whether mineral nitrogen is retained or lost. Thermophilic conditions (50–70 °C) accelerate organic matter degradation and are needed for sanitation, but they also enhance NH_3 transfer from the liquid phase to the gas phase and inhibit many nitrifiers, thereby increasing the risk of $\text{NH}_4^+\text{-N}$ accumulation and ammonia volatilization [38,39]. pH acts as a direct chemical control because the $\text{NH}_4^+/\text{NH}_3$ equilibrium shifts toward NH_3 as pH rises. Once pH exceeds roughly 8.0, volatilization can increase sharply [5]. Therefore, maintaining pH within a weakly alkaline range (7.0–8.0) is crucial for inhibiting ammonia volatilization. Aeration is equally important: insufficient aeration promotes anaerobic zones and denitrification, whereas excessive aeration strips heat, water, and NH_3 from the pile [40]. Maintaining oxygen concentration within 5–15% is the ideal range for aerobic metabolism.

Microorganisms mediate every major nitrogen transformation pathway during composting. The activity of ammonia-oxidizing and nitrite-oxidizing microorganisms determines the efficiency of nitrification, while diverse heterotrophs drive ammonification, assimilation, and humification [41]. As temperature, oxygen availability, pH, and substrate quality change, the microbial community also shifts, and those shifts can redirect nitrogen either toward stable retention or toward gaseous and liquid loss.

Importantly, these factors do not act independently but often exert synergistic effects on nitrogen loss. For NH_3 volatilization, pH and temperature are particularly coupled: an increase in pH shifts the $\text{NH}_4^+/\text{NH}_3$ equilibrium toward free NH_3 , while thermophilic temperatures reduce NH_3 solubility and enhance its transfer from the liquid phase to the gas phase according to temperature-dependent gas–liquid partitioning. Under these conditions, intensive aeration may further accelerate NH_3 stripping from the composting matrix. Similarly, moisture interacts with aeration by controlling free air space and oxygen diffusion; excessive moisture can create anaerobic microsites that favor denitrification and N_2O production, whereas insufficient moisture suppresses microbial assimilation and nitrification. Therefore, nitrogen retention depends on the coordinated optimization of C/N ratio, moisture, temperature, pH, and aeration rather than on the adjustment of any single factor alone.

3. Multiscale Strategies for Controlling Nitrogen Loss

Nitrogen loss during composting is a complex process driven by the coupling of multiple biotic and abiotic factors. Therefore, developing comprehensive mitigation strategies requires a multi-scale approach spanning microscopic, mesoscopic, and macroscopic levels. As illustrated in Figure 2, the multiscale control framework was established based on the major intervention points that influence nitrogen transformation and loss throughout the composting process. Feedstock pretreatment represents source-level regulation by modifying substrate properties such as C/N ratio, porosity, and adsorption capacity. Process regulation focuses on dynamic operational factors, including aeration, moisture, temperature, and pH, which directly affect microbial activity and nitrogen conversion pathways. Post-treatment aims to stabilize the nitrogen retained after the thermophilic phase and minimize secondary losses during curing, storage, transport, and land application. At the system scale, reactor design and engineering were included because they determine the resource recovery and engineering efficiency of retained nitrogen beyond individual process parameters. Policy and governance support was further considered because broader implementation of nitrogen-retention technologies depends on economic feasibility, environmental standards, and management incentives. Therefore, these five dimensions provide an integrated framework for linking mechanistic understanding with practical nitrogen-loss control strategies.

3.1. Feedstock Pretreatment and Source Control

Pretreatment of feedstock provides the first opportunity to reduce nitrogen loss because it defines the substrate environment in which subsequent microbial and physico-chemical processes occur. At this stage, the main objective is to optimize the initial matrix through physical, chemical, and biological measures so that NH_3 volatilization potential is reduced, denitrification risk is limited, and in subsequent stage nitrogen stabilization becomes more likely.

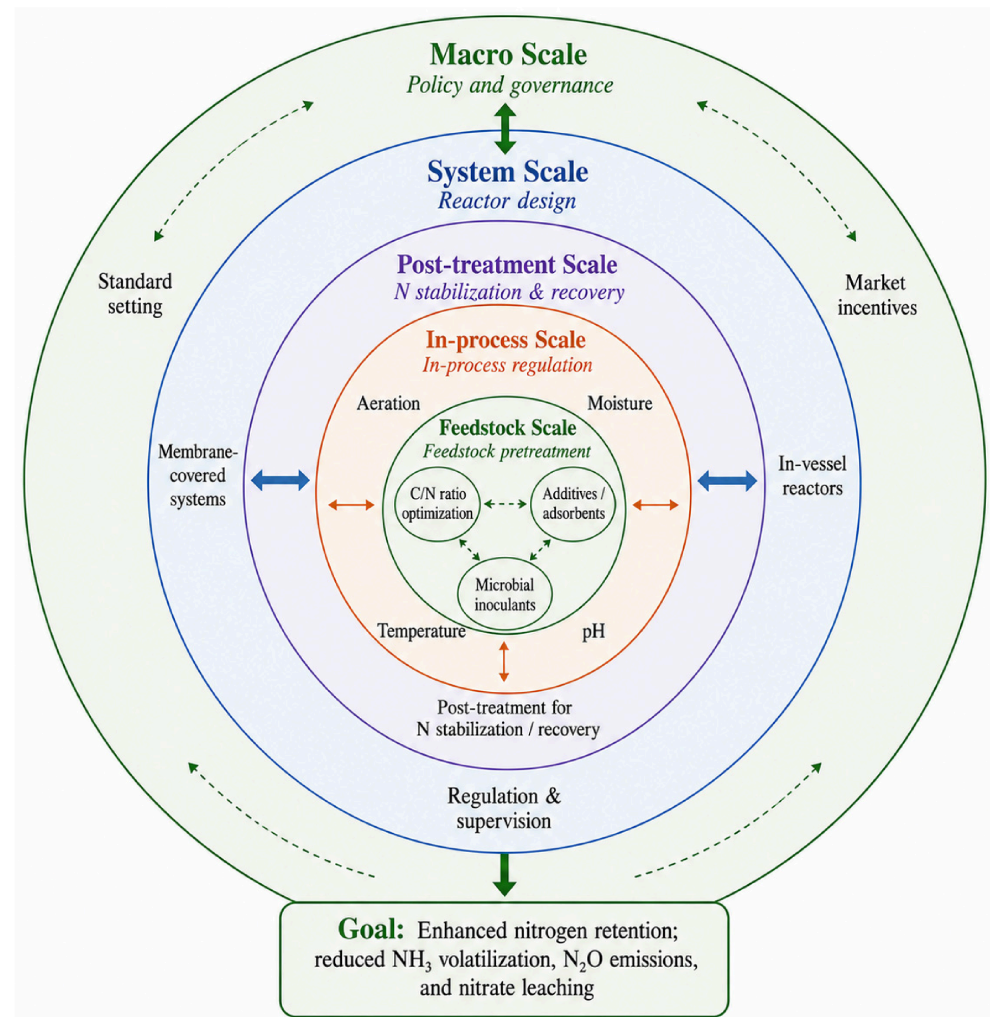


Figure 2. A multiscale organizational framework for mitigating nitrogen loss during aerobic composting, spanning feedstock micro-environment optimization, macroscopic process control, reactor engineering, and macro-level policy and governance.

Adjustment of the initial C/N ratio remains the most basic and most widely used source-control strategy. For nitrogen-rich materials such as livestock manure, co-composting with carbonaceous bulking agents such as straw, rice husk, sawdust, or corncob can reduce excess $\text{NH}_4^+\text{-N}$ formation and improve microbial immobilization. Synthesizing recent quantitative data reveals that optimizing the C/N ratio using agricultural residues generally yields a 30% to 70% reduction in overall nitrogen loss, heavily dependent on the carbon source's porosity and bioavailability. In chicken manure composting, adjusting the initial C/N ratio to 15 with wheat straw reduced nitrogen loss by 39.67% relative to the manure-only control [42]. In another study, increasing the initial C/N ratio from 18 to 22 by adding corn stover lowered total nitrogen loss from 38.62% to 32.57% [43]. Similarly, optimizing the mixing ratio of swine manure and corn stalks reduced NH_3 emissions by 64–71% [44]. These results also show that carbon quality matters: highly available carbon can immobilize nitrogen quickly, whereas more recalcitrant carbon acts more slowly.

Bulking agents also improve the physical structure of the composting matrix. By modifying the particle-size distribution, bulking agents regulate the balance between substrate accessibility and free air space: smaller particles provide a larger specific surface area and may accelerate ammonification, whereas excessively fine particles can reduce porosity and restrict oxygen diffusion. A well-aerated porous structure enhances oxygen penetration, reduces local compaction and waterlogging, and limits the formation of

anaerobic microsites where denitrification can occur. It also helps drain excess water and thereby reduces leachate-driven losses of soluble nitrogen. In pig-manure composting, replacing sawdust or corn stalks with spent mushroom substrate lowered total nitrogen loss from 35.69% and 19.42% to 11.16%, corresponding to relative reductions of 68.73% and 42.53%, respectively [45].

Functional amendments can further retain nitrogen by adsorption, ion exchange, or chemical fixation. Biochar is widely studied because its high surface area, porous structure, and oxygen-containing functional groups can adsorb NH_4^+ and NH_3 while also modifying pH and microbial habitat. During poultry-manure composting, different plant-derived biochars reduced NH_3 emissions by 1.26–36.38% and N_2O emissions by 35.74–52.82% [46]. In a chicken manure–corn straw system, adding 8% biochar reduced cumulative NH_3 emissions by 54.83% and increased the final total nitrogen content by 22.40% [47]. Mineral adsorbents such as zeolite and bentonite are also effective because their cation-exchange capacity allows selective retention of NH_4^+ . In chicken manure–straw composting, 10% zeolite lowered cumulative NH_3 and N_2O emissions by 28% and 55%, respectively, while increasing nitrate content by 17% [48]. In pig-manure composting, bentonite reduced NH_3 and N_2O emissions by 18.82% and 72.56%, respectively [49]. Acidifying or reactive additives such as superphosphate can also suppress NH_3 loss by lowering pH and converting free ammonia into more stable forms; in pig manure composting, superphosphate reduced cumulative NH_3 emissions by 23.8–48.1% [50].

Chemical precipitation offers another route for nitrogen conservation. When magnesium- and phosphorus-bearing reagents are added, NH_4^+ can be converted into struvite ($\text{MgNH}_4\text{PO}_4 \cdot 6\text{H}_2\text{O}$), a stable slow-release fertilizer phase. In pig manure–corn straw composting, the combined addition of calcium superphosphate and $\text{Mg}(\text{OH})_2$ promoted struvite formation, reduced cumulative NH_3 volatilization and total nitrogen loss by 41.78% and 13.27%, respectively, and increased both NH_4^+ -N and NO_3^- -N in the final product [51].

Biological inoculation is increasingly used to redirect nitrogen transformation. Nitrifying consortia can accelerate the conversion of NH_4^+ to oxidized nitrogen forms and thereby reduce gaseous loss. In cow-manure composting, inoculation with a consortium of psychrophilic and thermophilic nitrifiers increased NO_3^- formation by 77.87–82.35% while reducing NH_3 and N_2O emissions by 48.89% and 20.05%, respectively [52]. Lignocellulose-degrading inoculants can also promote carbon turnover and indirectly improve nitrogen retention; one study reported 25.9% lower NH_3 emissions and 34.98% lower N_2O emissions after inoculation with lignocellulose-degrading microorganisms [53]. Acid-producing consortia provide a different mechanism. A synthetic lactic-acid-bacteria consortium reduced NH_3 emissions from livestock waste by 95.5% by lowering pH, shifting the $\text{NH}_4^+/\text{NH}_3$ equilibrium toward NH_4^+ , and suppressing ureolytic bacteria [54].

3.2. Process Optimization

Process optimization aims to create conditions under which microbial assimilation, nitrification, and humification can proceed efficiently while pathways that drive NH_3 , N_2O , and leachate loss are constrained. Temperature control is central to this goal. A thermophilic phase (45–65 °C) is still required for sanitation and rapid degradation, but excessively high or prolonged temperatures intensify NH_3 volatilization and suppress many nitrifiers [10,39,55]. Once hygiene requirements have been met, the composting system should be gradually shifted from thermophilic conditions to a mesophilic cooling/maturation range that is more favorable for nitrification and nitrogen stabilization. Nitrification generally becomes more favorable when the temperature declines to around 35–45 °C, preferably approaching below 40 °C [56]. Because temperature is inseparable

from aeration and moisture, it should be managed as part of an integrated control strategy rather than as an isolated variable.

Aeration is one of the most influential operating variables in aerobic composting because it controls oxygen supply, heat removal, moisture exchange, and the stripping of volatile compounds [10]. Adequate aeration is needed to avoid anaerobic microsites and limit denitrification, yet excessive continuous aeration can markedly increase NH_3 loss. In chicken manure composting, an aeration rate of $0.1 \text{ m}^3 \cdot \text{h}^{-1}$ achieved maturity and humification while also producing the lowest NH_3 emission among the tested treatments [40]. In cow manure composting, two intermittent-aeration regimes reduced cumulative NH_3 emissions by 24.37% and 19.27% and total nitrogen losses by 9.07% and 6.10%, respectively, compared with continuous aeration, although N_2O emissions increased by 22.22% and 43.14% [57]. These findings support the use of intermittent or feedback-controlled aeration rather than fixed high-rate continuous ventilation. However, intermittent aeration should not be regarded as universally beneficial, because reduced NH_3 stripping may create transient oxygen-limited microsites that increase N_2O emissions; therefore, its environmental benefit should be assessed using both nitrogen-retention and CO_2 -equivalent indicators. This approach is becoming more realistic in practice: a real-time gas sensor network recently achieved O_2 accuracy within $\pm 1.5\%$ and helped increase the nitrogen content of the final compost by 31.7% under optimized control [58].

Moisture control is equally important because water availability shapes both microbial activity and oxygen diffusion. In most aerobic systems, a moisture content of roughly 55–65% provides a workable balance between microbial metabolism and air-filled porosity [10]. When moisture is too high, oxygen transfer declines and denitrification risk increases; when it is too low, decomposition slows because of water stress. In rapid kitchen-waste composting, total nitrogen loss ranged from 18.81% to 37.85% of the initial nitrogen, and NH_3 accounted for 11.09–35.03%; based on the combined criteria of maturity and gaseous-emission control, the recommended moisture range was 60–65% [59]. In microbial-agent-enhanced chicken manure composting, an initial moisture content of 53% produced the highest peak temperature, the longest thermophilic period, and better nitrogen retention than drier or wetter treatments [60]. Liquid-phase recirculation can also help: a condensation-return composting system reduced NH_3 emissions by 59.3% and increased the total nitrogen content of the final product by 19.4% [61].

Because pH directly governs the $\text{NH}_4^+/\text{NH}_3$ equilibrium, pH management has long been considered a potential tool for nitrogen conservation. In practice, however, bulk acidification must be used cautiously because excessive acidification can delay degradation and may even increase N_2O release under some conditions. For example, acidifying manure to pH 5 prolonged degradation by 7–10 d and increased N_2O emissions by 18.6%, whereas acidification to pH 6 reduced N_2O and CH_4 emissions by 17.6% and 20%, respectively, without impairing maturity [62]. Indirect approaches are often more practical. Adding 20% apple pomace during pig-manure composting reduced cumulative NH_3 and N_2O emissions by 57% and 24%, respectively, while increasing the final total nitrogen content by 19% [63].

In windrow systems, turning is the main physical intervention used to redistribute heat, moisture, oxygen, and substrates, but the turning schedule should be matched to process conditions rather than fixed by calendar alone. Excessive turning promotes heat loss and NH_3 stripping, whereas insufficient turning increases the risk of compaction and anaerobic zones. In chicken manure–soybean straw composting, turning every 5 d reduced NH_3 emissions by 11.42–18.95% relative to 1 or 3 d intervals and lowered total nitrogen loss compared with both more frequent and less frequent turning [64]. Model-based control offers a further step toward precision management: a kinetics-based turning strategy prolonged the period above 50°C by 2 d and improved line efficiency by more

than 10% relative to a fixed 4 d schedule [65]. Taken together, these results suggest that turning should be viewed as a dynamic control variable rather than a routine operation.

3.3. Post-Treatment Nitrogen Stabilization and Resource Recovery

Post-treatment management should stabilize the nitrogen retained after the thermophilic stage and prevent secondary losses during curing, storage, transport, and land application. Among the available options, curing is particularly important because it extends maturation under lower temperatures and lower oxygen demand, allowing the compost to undergo slower decomposition and further organic matter stabilization. During this stage, continued microbial transformation and humification can also promote nitrogen retention and stabilization in the final compost product [66,67]. During curing, the microbial community shifts from thermophilic populations toward mesophilic decomposers, and fungi and actinomycetes become increasingly important for degrading recalcitrant lignocellulosic fractions and promoting humification [68,69]. As humification proceeds, part of the retained nitrogen is incorporated into humic substances and other relatively stable organic nitrogen pools [70]. At the same time, nitrification becomes more active as temperature declines under aerobic conditions, which helps convert residual NH_4^+ to NO_3^- [10]. This does not eliminate risk, however, because excessive nitrate accumulation may interfere with humic-acid formation and can increase the risk of leaching if curing proceeds under wet conditions [71]. Deep nitrogen stabilization during curing therefore depends on adequate curing time together with careful control of aeration, moisture, and rainfall exposure.

Once curing is complete, mature compost can be upgraded into standardized commercial products that improve handling and may further reduce secondary nitrogen loss. Pelletization or granulation increases bulk density, suppresses dust formation, facilitates storage and mechanized application, and can alter the release pattern of compost-derived nitrogen in soil [72,73]. During granulation, the addition of sorptive or nitrogen-retaining amendments such as bentonite-type minerals or humic substances may further enhance nitrogen stability [24,74]. Cured compost can also be blended with mineral nutrients to produce organo-mineral fertilizers or specialized substrates with more controlled nutrient release [75]. Where ammonium-rich side streams are available, magnesium- and phosphorus-based reagents can recover nitrogen as struvite, a recyclable slow-release fertilizer. Recent work on agricultural waste streams has shown high ammoniacal-nitrogen recovery during struvite production and lower off-site nutrient-loss risk than with readily soluble fertilizers [76,77].

3.4. Reactor Innovation and High-Efficiency Composting Technology

Reactor innovation has shifted agricultural-waste composting from empirically managed open piles toward semi-closed or closed systems with improved control of heat transfer, gas exchange, and liquid collection (Table 2). From the standpoint of nitrogen conservation, the main benefit of these systems is not only faster stabilization, but also tighter control over NH_3 stripping, denitrification-prone microsites, and opportunities for nitrogen recovery.

Table 2. Commonly used aerobic composting systems for agricultural waste and their engineering characteristics.

Composting System	Common Construction Materials	Typical Processing Capacity	Cost Relative to Pile/Windrow Composting	Key Features for Nitrogen Control	Ref.
Open Pile/turned windrow (<i>Baseline</i>)	Soil/Concrete pad; optional roof/cover or drainage system; turning by front-end loader or windrow turner	Farm to centralized operations; capacity is expanded by windrow length, width, and number; active composting often lasts several weeks	Baseline; lowest capital cost, but usually higher land requirement, weather exposure, and turning labor	Simple and flexible, but limited control of oxygen, moisture, and temperature; higher risk of NH ₃ volatilization, odor, leachate, and N ₂ O formation	[78–80]
Aerated static pile	Concrete/asphalt pad; perforated PVC/HDPE or metal aeration pipes; blower, timer or temperature sensor; optional cover and biofilter/scrubber	Farm to municipal/industrial scale; scalable by increasing pile number or aeration area; Active composting can be shortened to about 3–5 weeks when air distribution and mixing are adequate	Low to moderate; higher than open piles due to aeration equipment and electricity, but lower turning labor and often smaller footprint	Improved oxygen supply and reduces anaerobic microsites and denitrification risk; negative aeration can support odor and NH ₃ capture, whereas excessive airflow may increase NH ₃ stripping and water loss	[78,79,81]
Membrane-Covered aerated pile (<i>Semi-closed</i>)	Aerated pile on concrete/asphalt pad covered with a semi-permeable membrane, commonly ePTFE/PTFE-based with protective textile layers; under-pile aeration, sealing/weights, and sensors may be used	Modular farm or centralized composting systems; capacity is increased by adding covered modules or enlarging the aerated pad	Moderate to high; higher than simple aerated piles because of membrane and control equipment	Conserves heat and moisture, improves pile homogeneity, and restricts direct gas exchange; reduces NH ₃ and N ₂ O losses when membrane properties and aeration rate are optimized	[82–85]
Enclosed channel/tunnel/agitated-bed reactor (<i>Fully closed</i>)	Reinforced-concrete channels, tunnels, or beds; steel or insulated doors/panels; in-floor aeration, exhaust ducts, leachate collection, biofilter or scrubber, and automatic turning or moving-floor equipment	Medium to large centralized facilities; batch or semi-continuous operation; capacity depends on the number and dimensions of channels/tunnels and the residence time	High; requires civil construction, blowers, automatic turning, exhaust treatment, leachate management, and routine maintenance	Strong control of temperature, aeration, exhaust gas, and leachate; suitable for integrating NH ₃ capture or recirculation, and more uniform nitrification or humification	[78,80]
Rotary drum/container/silo in-vessel reactor (<i>Fully closed</i>)	Steel, stainless-steel, fiberglass-reinforced plastic, or reinforced-concrete vessel; insulation; mechanical mixing or rotating drum; forced aeration; condensate/exhaust collection; automated control system	Small farm modular units to industrial reactors; suitable where land availability is limited	High to very high; highest capital, energy, automation, and maintenance costs, but smaller footprint, shorter active phase, and lower manual handling	Strongest control over oxygen, temperature, exhaust gas, and condensate; suitable for coupling composting with NH ₃ capture, condensate return	[78,86]

Note: Capacity and cost are presented as typical relative categories rather than fixed values, because actual values depend on feedstock type, moisture content, pile/reactor size, residence time, aeration design, automation level, emission-control requirements, land price, labor, and local construction costs. Open pile/windrow composting is used as the baseline for relative cost comparison. Italicized terms “*Semi-closed*” and “*Fully closed*” indicate the degree of system enclosure relative to open pile/windrow composting.

Membrane-covered composting is a representative semi-closed option. Depending on membrane characteristics and operating conditions, it can substantially reduce the exchange of heat, moisture, and nitrogenous gases with the surrounding environment. Quantitative nitrogen-balance analysis showed that membrane-covered aerobic composting reduced total nitrogen loss by 33.24–50.07% relative to uncovered composting [87]. A comparative study also reported 53.9% lower NH_3 emissions and 71.3% lower N_2O emissions under semi-permeable membrane covering [82]. At the same time, membrane systems are not uniformly beneficial: another study found a 15.43–34.00% decrease in total nitrogen loss but a 16.91–90.13% increase in NH_3 emissions, indicating that membrane properties and aeration strategy must be optimized together [83].

Fully or partially enclosed in-vessel systems offer even tighter operational control because aeration, temperature, exhaust gas, and condensate can be managed more precisely than in conventional windrows. In a closed aerobic composter treating laying hen manure, gas-permeable membrane capture with sulfuric acid recovered 0.61–0.65 kg total ammonia nitrogen (TAN), and the in-reactor membrane configuration achieved a recovery rate of $6.9 \text{ g TAN m}^{-2} \cdot \text{d}^{-1}$ compared with $1.9 \text{ g TAN m}^{-2} \cdot \text{d}^{-1}$ for the external module [88]. Likewise, a condensation-return composting system reduced NH_3 emissions by 59.3% and increased the total nitrogen content of the final product by 19.4% [60]. These examples show that reactor design becomes especially effective when it is coupled with ammonia capture or liquid-phase recirculation.

Another major trend is the integration of controlled aeration with intelligent ventilation design. Rather than relying on fixed, experience-based operation, modern systems increasingly use staged or intermittent aeration to balance oxygen supply, heat retention, and ammonia stripping. In reactor composting of cow manure and corn stalks, intermittent aeration reduced cumulative NH_3 emissions by 24.37% and total nitrogen loss by 9.07% relative to continuous aeration [57]. In semi-permeable membrane-covered vegetable-waste composting, a multichannel ventilation mode reduced NH_3 , N_2O , and CH_4 emissions by 22.57%, 21.52%, and 32.67%, respectively, compared with single-bottom ventilation [89]. Together, these results suggest that the real value of reactor innovation lies in combining semi-/closed structures, controlled ventilation, and nitrogen capture or recirculation, thereby shifting composting from passive emission reduction toward active pathway regulation and partial nutrient recovery.

Overall, reactor innovation is most valuable when semi- or fully enclosed structures are combined with controlled ventilation, gas capture, and liquid recirculation. Under those conditions, nitrogen management shifts from simple emission reduction toward deliberate pathway regulation and partial nutrient recovery.

3.5. Policy and Governance Strategies

From a policy and governance perspective, nitrogen loss during aerobic composting of agricultural waste should be treated not merely as a process-control issue, but as a nutrient-cycling challenge that spans waste treatment, fertilizer production, and farmland application. Standard setting is a priority. A dual framework covering both compost product quality and process emissions is warranted because market acceptance remains constrained by variability in nutrient content, uncertainty in nutrient release, and concerns over contaminants in recycled nutrient products [90]. Accordingly, compost standards should move beyond conventional maturity indicators and include nitrogen-related metrics such as total nitrogen, the $\text{NH}_4^+/\text{NO}_3^-$ ratio, and, where feasible, indicators of nitrogen stability. Process-oriented standards should also include NH_3 and N_2O accounting, because composting is a source of both air pollutants and greenhouse gases. A recent critical review compiled 388 emission factors from 46 studies, highlighting the large variability in reported

values and the need for more consistent accounting methods [91]; it identified N_2O as the dominant contributor for nitrogen-rich feedstocks such as manure, and NH_3 and VOCs as key air-pollutant emissions requiring process-level accounting. Standardized protocols would strengthen differentiated regulation of large-scale plants, support best-management-practice certification for decentralized systems, and allow more credible comparisons across technological pathways [91,92].

Regulation should combine mandatory environmental safeguards with market-based incentives. A recent review of policy impacts on nutrient circularity identified manure management and nutrient-recycling technologies as recurrent policy targets and showed that economic incentives, certification schemes, and coordinated policy frameworks are major drivers of adoption [93]. Other recent analyses likewise emphasize that supportive policies, economic feasibility, and public acceptance are all important for the wider uptake of recycled nutrient products [90]. In practical terms, this means that low-nitrogen-loss composting technologies should be incorporated into permitting and impact-assessment frameworks, while subsidies, tax incentives, green public procurement, and organic or green product certification can be used to reward compost products with demonstrably higher nitrogen retention and lower process emissions. Representative examples already exist in several countries and regions. In China, the Pilot Program of Green Planting–Breeding Circular Agriculture uses central fiscal reward subsidies to support the local return of livestock manure-derived fertilizers to farmland by funding specialized service providers for manure collection, treatment, and field application [94]. The program also requires harmless treatment and composting before land application and encourages scientifically determined manure-fertilizer application rates and chemical fertilizer substitution. In the United States, USDA (United States Department of Agriculture) NRCS (Natural Resources Conservation Service) programs such as EQIP (Environmental Quality Incentives Program) support conservation practices including composting facilities and nutrient management, which promote the transformation of manure and other organic wastes into stable soil amendments and improve the timing, source, rate, and placement of nutrients to reduce environmental impacts, including greenhouse gas emissions [95]. At the EU level, CAP (Common Agricultural Policy) 2023–2027 eco-schemes and rural development interventions reward sustainable nutrient management practices, including reduced use of inorganic fertilizers, promotion of organic fertilization, and best practices that limit nutrient losses to air and water [96]. These examples indicate that policy incentives can support nitrogen-retention-oriented composting not only by promoting the production and use of organic fertilizers, but also by encouraging nutrient management practices that reduce nitrogen losses and nitrogenous emissions such as NH_3 and N_2O .

4. Challenges and Future Perspectives

To highlight the practical relevance of the control strategies discussed above, Table 3 summarizes representative approaches for reducing nitrogen loss, including their intervention points, main mechanisms, reported effects on nitrogen retention or nitrogenous emission mitigation, and key limitations. The summarized data show that the effectiveness of mitigation strategies varies substantially across intervention scales. At the feedstock level, optimization of the initial C/N ratio reduced total nitrogen loss by 30–68% and NH_3 emissions by 64–71%. Biochar addition reduced NH_3 emissions by 36–55% and N_2O emissions by 35–53%, whereas mineral adsorbents such as zeolite and bentonite reduced NH_3 emissions by 18–28% and N_2O emissions by 55–73%. At the process-regulation level, intermittent aeration produced more moderate but operationally accessible benefits, reducing NH_3 emissions by 19–24% and total nitrogen loss by 6–9% relative to continuous aeration. At the reactor scale, membrane-covered systems achieved reported reductions

of 33–50% in total nitrogen loss and approximately 71% in N₂O emissions, while closed in-vessel systems coupled with acid scrubbing or condensate return reduced NH₃ emissions by approximately 59% and increased the total nitrogen content of the final compost by approximately 19%.

Table 3. Quantitative synthesis of the effectiveness of main mitigation strategies on nitrogen loss and greenhouse gas emissions during aerobic composting.

Scale of Control	Mitigation Strategy	Specific Intervention	Main Mechanisms	Advantages	Limitations	Typical Quantitative Outcomes (Reductions vs. Control)	Ref.
Feedstock (Pretreatment)	C/N Ratio Optimization	Adding wheat straw, corn stover, or stalks (Initial C/N ~15–25)	Balances carbon availability; promotes microbial N assimilation; improves matrix porosity.	Low cost; improves porosity and N retention	May increase volume; risk of delayed maturity	Total N loss: –30–68%; NH ₃ emissions: –64–71%	[42–45]
	Carbonaceous Additives	Biochar (8–10% w/w)	High surface area for NH ₄ ⁺ adsorption; modifies pH buffering; shifts microbial habitat.	Easy application; improves nutrient retention	Cost and effectiveness vary	NH ₃ emissions: –36–55%; N ₂ O emissions: –35–53%; Total N content: +22%	[46,47]
	Mineral Adsorbents	Zeolite/Bentonite (10% w/w)	Cation-exchange capacity (CEC) allows selective retention of NH ₄ ⁺ .	Rapid NH ₃ reduction; enhances N fixation	Reagent cost; salinity or pH risks	NH ₃ emissions: –18–28%; N ₂ O emissions: –55–73%	[48,49]
	Chemical Fixation	Superphosphate + Mg(OH) ₂	Induces struvite (MgNH ₄ PO ₄ ·6H ₂ O) precipitation.			NH ₃ emissions: –23–48%; Total N loss: –13%	[50,51]
	Microbial Inoculation	Nitrifying consortia/Lignocellulose degraders	Accelerates NH ₄ ⁺ to NO ₃ [–] conversion; lowers pH via organic acids.	Promotes maturation and biological N retention	Unstable performance at field scale	NH ₃ emissions: –25–95%; N ₂ O emissions: –20–35%; NO ₃ [–] formation: +77–82%	[52–54]
Process (Regulation)	Aeration Management	Intermittent aeration vs. Continuous high-rate	Avoids excessive stripping of heat/NH ₃ ; maintains sufficient O ₂ .	Improves O ₂ supply and process stability	Excess aeration strips NH ₃ ; low aeration increases anaerobic emissions	NH ₃ emissions: –19–24%; Total N loss: –6–9%	[57]
	Turning Frequency	Optimized interval (e.g., every 5 days)	Prevents physical NH ₃ stripping while avoiding anaerobic pockets.			NH ₃ emissions: –11–19%	[64]
Reactor (Engineering)	Membrane-Covering	Semi-permeable membranes	Traps gases; promotes condensation and N recirculation.	Improves heat/moisture retention; reduces odor and emissions	Cost, maintenance, and membrane-aging concerns	Total N loss: –33–50%; N ₂ O emissions: –~71%	[82,83,87]
	Closed In-vessel	Reactor with acid-scrubbing or condensation return	Actively captures off-gas and recovers NH ₃ .	High controllability; enables emission reduction and N recovery	High investment, energy use	NH ₃ emissions: –~59%; Total N content: +19%	[60,88]

Note: “+” indicates an increase, “–” indicates a reduction. Values are approximations synthesized from the cited experimental literature.

Despite these advances, several major challenges remain. Many control measures still involve pollution swapping rather than complete mitigation. For instance, interventions that suppress NH₃ volatilization may under some conditions increase N₂O release, shifting rather than eliminating the environmental burden. Other measures create engineering trade-offs. Large additions of bulking agents can reduce nitrogen loss at the source, yet they also lower volumetric loading and may weaken reactor productivity. Likewise, effective additives such as biochar and zeolite remain costly at scale, and their long-term

field performance and possible secondary environmental risks are not yet fully resolved. Future economic evaluations should integrate cost–benefit analysis, techno-economic analysis, and life-cycle assessment, considering additive costs, fertilizer replacement value, emission-reduction benefits, carbon-credit potential, and environmental trade-offs. Although membrane-covered composting can improve process control and reduce nitrogen losses, the long-term durability of synthetic ePTFE/PTFE-based membranes and their potential contribution to microplastic contamination in compost-amended soils should be further evaluated in future studies. High-precision control strategies improve nitrogen retention, but they often require more complex equipment, more skilled operation, and higher capital and maintenance costs.

These limitations mean that mitigation strategies cannot be judged solely by laboratory performance. They must also be tested against practical engineering criteria and assessed with consistent system boundaries. A recent review of life cycle assessment studies on composting identified 456 publications from 2010 to 2022, among which 56 were selected for detailed analysis because of their relevance and methodological completeness [92]. The practical information reported in these studies indicates that the environmental performance of composting is strongly affected by system boundaries, functional units, emission-factor selection, direct NH_3 and N_2O emissions, and whether the final compost product is credited for replacing mineral fertilizers or soil amendments. Therefore, nitrogen retention technologies should not be evaluated solely according to plant-level nitrogen conservation, but also according to whether the retained nitrogen can be effectively stabilized, transported, and used in farmland while reducing synthetic nitrogen fertilizer demand and nitrogenous emissions. Likewise, reported gaseous emission factors for composting vary substantially among studies because they are affected by feedstock composition, composting technology, aeration and moisture management, temperature regime, measurement method, functional unit, and system boundary. This variability limits the direct use of unharmonized literature-derived emission factors in regulatory inventories, policy evaluation, and cross-study comparison; therefore, site-, substrate-, and system-specific measurements or harmonized reporting approaches are needed [91,92,97]. This points to an urgent need for standardized NH_3 and N_2O accounting protocols and differentiated emission benchmarks that can support technology selection, performance assessment, and evidence-based policymaking.

Future research should therefore move beyond single-factor optimization and place greater emphasis on multiscale coupling and intelligent regulation. In particular, the interactions among microbial nitrogen transformation pathways, substrate properties, in-process regulation, and reactor configurations should be further explored, as they jointly determine nitrogen retention and nitrogenous gas emissions at the microbial, process, and system levels [98]. Meanwhile, Internet of Things (IoT) technologies, online sensing, and machine-learning-assisted control provide promising opportunities for data-driven composting systems by enabling real-time monitoring and adaptive regulation of key process parameters, such as temperature, moisture, oxygen, and NH_3 emissions [99,100]. However, their practical application still requires further improvement in sensor durability, model generalizability, and system-level integration under diverse composting conditions [2,101]. For large-scale deployment, however, such systems must be robust, affordable, and easy to operate, and they should be evaluated with combined life cycle assessment and techno-economic analysis rather than by short-term emission data alone [102,103].

5. Conclusions

Nitrogen loss remains one of the main constraints on the aerobic composting of agricultural waste because it lowers fertilizer value and increases environmental impacts.

Across current studies, NH_3 volatilization is the dominant loss pathway, whereas nitrate leaching and denitrification-related emissions, especially N_2O , make smaller but still important contributions to nitrogen loss and environmental risk.

Based on the quantitative synthesis summarized in this review, feedstock-level regulation and functional additives generally show strong potential for reducing NH_3 volatilization and total nitrogen loss, whereas reactor innovation, nitrogen recovery, and intelligent control provide broader opportunities for stabilizing process performance and improving nutrient recovery. However, no single strategy can be regarded as universally optimal, because the effectiveness of each approach depends strongly on feedstock type, composting scale, climatic conditions, and operational management.

Current evidence also shows that many promising strategies are still limited by cost uncertainty, substrate-dependent performance, insufficient full-scale validation, and limited cost–benefit assessment. Future work should therefore focus on clarifying multiscale nitrogen-transformation mechanisms, developing low-cost and easy-to-operate intelligent regulation systems, and applying integrated evaluation frameworks that jointly consider process performance, environmental burdens, and economic feasibility. Overall, multiscale nitrogen-loss control can help shift agricultural-waste composting from passive waste stabilization toward active nitrogen conservation, emission mitigation, and circular nutrient management.

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References

1. Lackner, M.; Besharati, M. Agricultural waste: Challenges and solutions, a review. *Waste* **2025**, *3*, 18. [\[CrossRef\]](#)
2. Liu, B.; Zhang, K.; Wei, Y.; Ding, G.; Xu, T.; Zhang, L.; Li, J. Towards data-driven smart composting techniques and control systems. *Bioresour. Technol.* **2026**, *440*, 133514. [\[CrossRef\]](#) [\[PubMed\]](#)
3. Zhao, S.; Schmidt, S.; Qin, W.; Li, J.; Li, G.; Zhang, W. Towards the circular nitrogen economy—A global meta-analysis of composting technologies reveals much potential for mitigating nitrogen losses. *Sci. Total Environ.* **2020**, *704*, 135401. [\[CrossRef\]](#) [\[PubMed\]](#)
4. Zhao, L.; Huang, Y.; Ran, X.; Xu, Y.; Chen, Y.; Wu, C.; Tang, J. Nitrogen transformation mechanisms and compost quality assessment in sustainable mesophilic aerobic composting of agricultural waste. *Sustainability* **2025**, *17*, 575. [\[CrossRef\]](#)
5. Mo, J.; Xin, L.; Zhao, C.; Qin, Y.; Nan, Q.; Mei, Q.; Wu, W. Reducing nitrogen loss during kitchen waste composting using a bioaugmented mechanical process with low pH and enhanced ammonia assimilation. *Bioresour. Technol.* **2023**, *372*, 128664. [\[CrossRef\]](#) [\[PubMed\]](#)
6. Ding, J.; van der A, R.; Eskes, H.; Dammers, E.; Shephard, M.; Wichink Kruit, R.; Guevara, M.; Tarrason, L. Ammonia emission estimates using CrIS satellite observations over Europe. *Atmos. Chem. Phys.* **2024**, *24*, 10583–10599. [\[CrossRef\]](#)
7. IPCC. *Climate Change 2021: The Physical Science Basis: Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*; Cambridge University Press: Cambridge, UK; New York, NY, USA, 2021.

8. Wang, Y.; Liu, Y.; Xia, L.; Akiyama, H.; Chen, X.; Chen, J.; Fang, Y.; Vancov, T.; Li, Y.; Yao, Y.; et al. Accounting for differences between crops and regions reduces estimates of nitrate leaching from nitrogen-fertilized soils. *Commun. Earth Environ.* **2025**, *6*, 29. [\[CrossRef\]](#)
9. Chen, J.; Jin, C.; Sun, S.; Yang, D.; He, Y.; Gan, P.; Nalume, W.G.; Ma, Y.; He, W.; Li, G. Recognizing the challenges of composting: Critical strategies for control, recycling, and valorization of nitrogen loss. *Resour. Conserv. Recycl.* **2023**, *198*, 107172. [\[CrossRef\]](#)
10. Hoang, H.G.; Thuy, B.T.P.; Lin, C.; Vo, D.-V.N.; Tran, H.T.; Bahari, M.B.; Le, V.G.; Vu, C.T. The nitrogen cycle and mitigation strategies for nitrogen loss during organic waste composting: A review. *Chemosphere* **2022**, *300*, 134514. [\[CrossRef\]](#) [\[PubMed\]](#)
11. Hu, X.; Jing, Y.; Fu, N.; Wang, Y.; Qin, D.; Guo, X.; Wang, Y.; Wan, J. New insight into bacterial communities of chicken manure composting under increased carbon to nitrogen ratios: Spatial heterogeneity in diversity, networks, and assembly processes. *J. Environ. Chem. Eng.* **2024**, *12*, 113624. [\[CrossRef\]](#)
12. Cao, Y.; Wang, X.; Misselbrook, T.; Wang, R.; Zheng, X.; Ma, L. Quantification of N and C cycling during aerobic composting, including automated direct measurement of N₂, N₂O, NO, NH₃, CO₂ and CH₄ emissions. *Sci. Total Environ.* **2023**, *857*, 159177. [\[CrossRef\]](#) [\[PubMed\]](#)
13. Hao, L.; Li, Y.; Wang, S.; Wang, Y.; Hu, Y.; Xia, Y.; Qi, Z.; Gao, H.; Wei, D.; Li, W. Optimizing the cow manure-straw ratio to promote organic matter humification: Insights from three-dimensional fluorescence spectroscopy. *Plants* **2026**, *15*, 729. [\[CrossRef\]](#) [\[PubMed\]](#)
14. Cao, Y.; Bai, M.; Han, B.; Impraim, R.; Butterly, C.; Hu, H.; He, J.; Chen, D. Enhanced nitrogen retention by lignite during poultry litter composting. *J. Clean. Prod.* **2020**, *277*, 122422. [\[CrossRef\]](#)
15. Lin, J.; Mao, Y.; Mai, L.; Li, G.; Liu, H.; Peng, S.; Wang, D.; Li, Q.; Li, G. Accelerating the humification of mushroom waste by regulating nitrogen sources composition: Deciphering mechanism from bioavailability and molecular perspective. *Chemosphere* **2024**, *349*, 140816. [\[CrossRef\]](#) [\[PubMed\]](#)
16. Shen, B.; Zheng, X.; Zheng, L.; Yang, Y.; Xiao, D.; Sheng, Z.; Wang, Y.; Ai, B. Beyond the C/N ratio: The critical role of carbon bioavailability in aerobic composting of agricultural waste. *Clean Technol.* **2026**, *8*, 46. [\[CrossRef\]](#)
17. Huang, W.; Shi, H.; Weng, Q.; Ding, S.; Lou, L. Disparities and mechanisms of carbon and nitrogen conversion during food waste composting with different bulking agents. *J. Environ. Manag.* **2024**, *351*, 119629. [\[CrossRef\]](#) [\[PubMed\]](#)
18. Yang, H.; Zhang, H.; Qiu, H.; Anning, D.K.; Li, M.; Wang, Y.; Zhang, C. Effects of C/N ratio on lignocellulose degradation and enzyme activities in aerobic composting. *Horticulturae* **2021**, *7*, 482. [\[CrossRef\]](#)
19. Hu, Z.-T.; Huo, W.; Chen, Y.; Zhang, Q.; Hu, M.; Zheng, W.; Shao, Y.; Pan, Z.; Li, X.; Zhao, J. Humic substances derived from biomass waste during aerobic composting and hydrothermal treatment: A review. *Front. Bioeng. Biotechnol.* **2022**, *10*, 878686. [\[CrossRef\]](#) [\[PubMed\]](#)
20. Zhang, L.; Sun, X. Influence of bulking agents on physical, chemical, and microbiological properties during the two-stage composting of green waste. *Waste Manag.* **2016**, *48*, 115–126. [\[CrossRef\]](#) [\[PubMed\]](#)
21. Bernal, M.P.; Alburquerque, J.A.; Moral, R. Composting of animal manures and chemical criteria for compost maturity assessment. A review. *Bioresour. Technol.* **2009**, *100*, 5444–5453. [\[CrossRef\]](#) [\[PubMed\]](#)
22. Fan, T.; Zhang, X.; Wan, Y.; Deng, R.; Zhu, H.; Wang, X.; Wang, S.; Wang, X. Effect of different livestock manure ratios on the decomposition process of aerobic composting of wheat straw. *Agronomy* **2023**, *13*, 2916. [\[CrossRef\]](#)
23. Yu, H.; Xie, B.; Khan, R.; Yan, H.; Shen, G. The changes in functional marker genes associated with nitrogen biological transformation during organic-inorganic co-composting. *Bioresour. Technol.* **2020**, *295*, 122197. [\[CrossRef\]](#) [\[PubMed\]](#)
24. Shan, G.; Li, W.; Gao, Y.; Tan, W.; Xi, B. Additives for reducing nitrogen loss during composting: A review. *J. Clean. Prod.* **2021**, *307*, 127308. [\[CrossRef\]](#)
25. Jiang, T.; Schuchardt, F.; Li, G.X.; Guo, R.; Luo, Y.M. Gaseous emission during the composting of pig feces from Chinese Ganqinfen system. *Chemosphere* **2013**, *90*, 1545–1551. [\[CrossRef\]](#) [\[PubMed\]](#)
26. Mulbry, W.; Ahn, H. Greenhouse gas emissions during composting of dairy manure: Influence of the timing of pile mixing on total emissions. *Biosyst. Eng.* **2014**, *126*, 117–122. [\[CrossRef\]](#)
27. Wang, T.; Zhang, H.; Gao, D.; Yang, F.; Yang, S.; Jiang, T.; Zhang, Y.; Wei, Z. Anaerobic ammonium-oxidizing bacteria in cow manure composting. *J. Microbiol. Biotechnol.* **2017**, *27*, 1288–1299. [\[CrossRef\]](#) [\[PubMed\]](#)
28. Yang, X.; Liu, E.; Zhu, X.; Wang, H.; Liu, H.; Liu, X.; Dong, W. Impact of composting methods on nitrogen retention and losses during dairy manure composting. *Int. J. Environ. Res. Public Health* **2019**, *16*, 3324. [\[CrossRef\]](#) [\[PubMed\]](#)
29. Amuah, E.E.Y.; Fei-Baffoe, B.; Sackey, L.N.A.; Douth, N.B.; Kazapoe, R.W. A review of the principles of composting: Understanding the processes, methods, merits, and demerits. *Org. Agric.* **2022**, *12*, 547–562. [\[CrossRef\]](#)
30. Azim, K.; Soudi, B.; Boukhari, S.; Perissol, C.; Roussos, S.; Thami Alami, I. Composting parameters and compost quality: A literature review. *Org. Agric.* **2018**, *8*, 141–158.
31. Nemet, F.; Perić, K.; Lončarić, Z. Microbiological activities in the composting process—A review. *Columella* **2021**, *8*, 41–53. [\[CrossRef\]](#)

32. Xie, Y.; Zhou, L.; Dai, J.; Chen, J.; Yang, X.; Wang, X.; Wang, Z.; Feng, L. Effects of the C/N ratio on the microbial community and lignocellulose degradation, during branch waste composting. *Bioprocess Biosyst. Eng.* **2022**, *45*, 1163–1174. [\[CrossRef\]](#) [\[PubMed\]](#)
33. Shen, B.; Zheng, L.; Zheng, X.; Yang, Y.; Xiao, D.; Wang, Y.; Sheng, Z.; Ai, B. Insights from meta-analysis on carbon to nitrogen ratios in aerobic composting of agricultural residues. *Bioresour. Technol.* **2024**, *413*, 131416. [\[CrossRef\]](#) [\[PubMed\]](#)
34. Richard, T.L.; Hamelers, H.V.M.; Veeken, A.; Silva, T. Moisture relationships in composting processes. *Compost Sci. Util.* **2002**, *10*, 286–302. [\[CrossRef\]](#)
35. Kumar, S. Composting of municipal solid waste. *Crit. Rev. Biotechnol.* **2011**, *31*, 112–136. [\[PubMed\]](#)
36. Shi, M.; Zhao, Y.; Zhu, L.; Song, X.; Tang, Y.; Qi, H.; Cao, H.; Wei, Z. Denitrification during composting: Biochemistry, implication and perspective. *Int. Biodeterior. Biodegrad.* **2020**, *153*, 105043. [\[CrossRef\]](#)
37. Ayilara, M.S.; Olanrewaju, O.S.; Babalola, O.O.; Odeyemi, O. Waste management through composting: Challenges and potentials. *Sustainability* **2020**, *12*, 4456. [\[CrossRef\]](#)
38. Koyama, M.; Nagao, N.; Syukri, F.; Abd Rahim, A.; Kamarudin, M.S.; Toda, T.; Mitsuhashi, T.; Nakasaki, K. Effect of temperature on thermophilic composting of aquaculture sludge: NH₃ recovery, nitrogen mass balance, and microbial community dynamics. *Bioresour. Technol.* **2018**, *265*, 207–213. [\[CrossRef\]](#) [\[PubMed\]](#)
39. Zhao, Y.; Li, W.; Chen, L.; Meng, L.; Zhang, S. Impacts of adding thermotolerant nitrifying bacteria on nitrogenous gas emissions and bacterial community structure during sewage sludge composting. *Bioresour. Technol.* **2023**, *368*, 128359. [\[CrossRef\]](#) [\[PubMed\]](#)
40. Ma, R.; Liu, Y.; Wang, J.; Li, D.; Qi, C.; Li, G.; Yuan, J. Effects of oxygen levels on maturity, humification, and odor emissions during chicken manure composting. *J. Clean. Prod.* **2022**, *369*, 133326. [\[CrossRef\]](#)
41. Noor, R.S.; Shah, A.N.; Tahir, M.B.; Umair, M.; Nawaz, M.; Ali, A.; Ercisli, S.; Abdelsalam, N.R.; Ali, H.M.; Yang, S.H. Recent trends and advances in additive-mediated composting technology for agricultural waste resources: A comprehensive review. *ACS Omega* **2024**, *9*, 8632–8653. [\[CrossRef\]](#) [\[PubMed\]](#)
42. Cao, L.; Wang, Y.; Wang, Y.; Li, P.; Zheng, K.; Liu, J.; Li, H. Effects of wheat straw addition on nitrogen emission reduction and bacterial community during chicken manure composting. *J. Agro-Environ. Sci.* **2023**, *42*, 2560–2569.
43. Ma, R.; Li, D.; Qi, C.; Li, G.; Wang, G.; Liu, Y.; Sun, S.; Yuan, J. Effects of C/N ratio on maturity and odor emission during chicken manure composting. *Trans. Chin. Soc. Agric. Eng.* **2020**, *36*, 194–202.
44. Shi, Y.; Gu, X.; Song, J.; Li, H.; Sun, C.; Wang, J.; Li, J.; Liu, W.; Bu, G.; Wang, H.; et al. Odor emissions and humification during composting of pig manure and cornstalks: Role of mixing proportions. *J. Environ. Chem. Eng.* **2025**, *13*, 117586. [\[CrossRef\]](#)
45. Sun, X.-P.; Lu, P.; Jiang, T.; Schuchardt, F.; Li, G.-X. Influence of bulking agents on CH₄, N₂O, and NH₃ emissions during rapid composting of pig manure from the Chinese Ganqinfen system. *J. Zhejiang Univ. Sci. B* **2014**, *15*, 353–364. [\[CrossRef\]](#) [\[PubMed\]](#)
46. Dang, R.; Cai, Y.; Li, J.; Kong, Y.; Jiang, T.; Chang, J.; Yao, S.; Yuan, J.; Li, G.; Wang, G. Biochar reduces gaseous emissions during poultry manure composting: Evidence from the evolution of associated functional genes. *J. Clean. Prod.* **2024**, *452*, 142060. [\[CrossRef\]](#)
47. Jiang, F.L.; Yang, J.N.; Qin, S.W.; Jiang, W.; Yang, S.J. Influencing mechanisms of different additives on ammonia–nitrogen emission during aerobic composting. *J. Mater. Cycles Waste Manag.* **2025**, *27*, 4252–4263. [\[CrossRef\]](#)
48. Wang, B.; Zhang, P.; Guo, X.; Xu, X.; Tian, J.; Li, G.; Zhang, J. Contribution of zeolite to nitrogen retention in chicken manure and straw compost: Reduction of NH₃ and N₂O emissions and increase of nitrate. *Bioresour. Technol.* **2024**, *391*, 129981. [\[CrossRef\]](#) [\[PubMed\]](#)
49. Guo, H.; Gu, J.; Wang, X.; Nasir, M.; Yu, J.; Lei, L.; Wang, J.; Zhao, W.; Dai, X. Beneficial effects of bacterial agent/bentonite on nitrogen transformation and microbial community dynamics during aerobic composting of pig manure. *Bioresour. Technol.* **2020**, *298*, 122384. [\[CrossRef\]](#) [\[PubMed\]](#)
50. Wu, J.; He, S.; Li, G.; Zhao, Z.; Wei, Y.; Lin, Z.; Tao, D. Reducing ammonia and greenhouse gas emission with adding high levels of superphosphate fertilizer during composting. *Environ. Sci. Pollut. Res.* **2019**, *26*, 30921–30929. [\[CrossRef\]](#) [\[PubMed\]](#)
51. Li, D.; Li, S.; Li, G.; Wang, K. Effects of additive on nitrogen loss during composting of pig manure and corn straw. *Trans. Chin. Soc. Agric. Eng.* **2016**, *32*, 260–267.
52. Xu, Z.; Li, R.; Tang, D.K.H.; Zhang, X.; Zhang, X.; Liu, H.; Quan, F. Enhancing nitrogen transformation and humification in cow manure composting through psychrophilic and thermophilic nitrifying bacterial consortium inoculation. *Bioresour. Technol.* **2024**, *413*, 131507. [\[CrossRef\]](#) [\[PubMed\]](#)
53. Yu, J.; Gu, J.; Wang, X.; Guo, H.; Wang, J.; Lei, L.; Zhao, W. Effects of inoculation with lignocellulose-degrading microorganisms on nitrogen conversion and denitrifying bacterial community during aerobic composting. *Bioresour. Technol.* **2020**, *313*, 123664. [\[CrossRef\]](#) [\[PubMed\]](#)
54. Liu, J.; Li, X.; Xu, Y.; Wu, Y.; Wang, R.; Zhang, X.; Hou, Y.; Qu, H.; Wang, L.; He, M.; et al. Highly efficient reduction of ammonia emissions from livestock waste by the synergy of novel manure acidification and inhibition of ureolytic bacteria. *Environ. Int.* **2023**, *172*, 107768. [\[CrossRef\]](#) [\[PubMed\]](#)

55. Xu, Z.; Li, R.; Liu, T.; Zhang, G.; Wu, S.; Xu, K.; Zhang, Y.; Wang, Q.; Kang, J.; Zhang, Z.; et al. Effect of inoculation with newly isolated thermotolerant ammonia-oxidizing bacteria on nitrogen conversion and microbial community during cattle manure composting. *J. Environ. Manag.* **2022**, *317*, 115474. [[CrossRef](#)] [[PubMed](#)]
56. Cáceres, R.; Malińska, K.; Marfà, O. Nitrification within composting: A review. *Waste Manag.* **2018**, *72*, 119–137. [[CrossRef](#)] [[PubMed](#)]
57. Wang, Y.; Qiu, H.; Li, M.; Ghanney, P. Influence of aeration method on gaseous emissions and the losses of the carbon and nitrogen during cow manure composting. *Appl. Sci.* **2021**, *11*, 11639. [[CrossRef](#)]
58. Naser, A.G.; Naw, N.M.; Zakaria, M.R.; Kassim, M.S.M.; Mutalovich, A.A.; Katibi, K.K. A real-time gas sensor network with adaptive feedback control for automated composting management. *Sustainability* **2025**, *17*, 10152. [[CrossRef](#)]
59. Tang, R.; Liu, Y.; Ma, R.; Zhang, L.; Li, Y.; Li, G.; Wang, D.; Lin, J.; Li, Q.; Yuan, J. Effect of moisture content, aeration rate, and C/N on maturity and gaseous emissions during kitchen waste rapid composting. *J. Environ. Manag.* **2023**, *326*, 116662. [[CrossRef](#)] [[PubMed](#)]
60. Li, M.-X.; He, X.-S.; Tang, J.; Li, X.; Zhao, R.; Tao, Y.-Q.; Wang, C.; Qiu, Z.-P. Influence of moisture content on chicken manure stabilization during microbial agent-enhanced composting. *Chemosphere* **2021**, *264*, 128549. [[CrossRef](#)] [[PubMed](#)]
61. Zhou, S.; Jia, P.; Xu, W.; Syed, S.A.; Zhang, Z. A novel composting system for mitigating ammonia emissions and producing nitrogen-rich organic fertilizer. *Bioresour. Technol.* **2023**, *386*, 129455. [[CrossRef](#)] [[PubMed](#)]
62. Cao, Y.; Wang, X.; Liu, L.; Velthof, G.L.; Misselbrook, T.; Bai, Z.; Ma, L. Acidification of manure reduces gaseous emissions and nutrient losses from subsequent composting process. *J. Environ. Manag.* **2020**, *264*, 110454. [[CrossRef](#)] [[PubMed](#)]
63. Mao, H.; Zhang, T.; Li, R.; Zhai, B.; Wang, Z.; Wang, Q.; Zhang, Z. Apple pomace improves the quality of pig manure aerobic compost by reducing emissions of NH₃ and N₂O. *Sci. Rep.* **2017**, *7*, 870. [[CrossRef](#)] [[PubMed](#)]
64. Ma, Q.; Li, Y.; Xue, J.; Cheng, D.; Li, Z. Effects of turning frequency on ammonia emission during the composting of chicken manure and soybean straw. *Molecules* **2022**, *27*, 472. [[CrossRef](#)] [[PubMed](#)]
65. Wang, J.; Mao, H.; Zhou, J.; Yao, C.; Wang, Y. Process control of a compost-reactor turning operation based on a composting kinetics model. *Processes* **2023**, *11*, 3206. [[CrossRef](#)]
66. Oshins, C.; Michel, F. The composting process. In *The Composting Handbook*; Elsevier: Amsterdam, The Netherlands, 2022; pp. 51–101.
67. López-González, J.A.; López, M.J.; Vargas-García, M.C.; Suárez-Estrella, F.; Jurado, M.; Moreno, J. Tracking organic matter and microbiota dynamics during the stages of lignocellulosic waste composting. *Bioresour. Technol.* **2013**, *146*, 574–584. [[CrossRef](#)] [[PubMed](#)]
68. Zhang, Y.; Chen, M.; Guo, J.; Liu, N.; Yi, W.; Yuan, Z.; Zeng, L. Study on dynamic changes of microbial community and lignocellulose transformation mechanism during green waste composting. *Eng. Life Sci.* **2022**, *22*, 376–390. [[CrossRef](#)] [[PubMed](#)]
69. Zhu, L.; Wang, X.; Liu, L.; Le, B.; Tan, C.; Dong, C.; Yao, X.; Hu, B. Fungi play a crucial role in sustaining microbial networks and accelerating organic matter mineralization and humification during thermophilic phase of composting. *Environ. Res.* **2024**, *254*, 119155. [[CrossRef](#)] [[PubMed](#)]
70. Su, J.; Zhan, Y.; Chang, Y.; Chang, S.; Luo, Y.; Chen, P.; Tao, X.; Chen, Y.; Yang, L.; Xu, T.; et al. Phosphate additives promote humic acid carbon and nitrogen skeleton formation by regulating precursors and composting bacterial communities. *Bioresour. Technol.* **2024**, *399*, 130617. [[CrossRef](#)] [[PubMed](#)]
71. Shi, M.; Wei, Z.; Wang, L.; Wu, J.; Zhang, D.; Wei, D.; Tang, Y.; Zhao, Y. Response of humic acid formation to elevated nitrate during chicken manure composting. *Bioresour. Technol.* **2018**, *258*, 390–394. [[CrossRef](#)] [[PubMed](#)]
72. Papandrea, S.F.; Cataldo, M.F.; Palma, A.; Gallucci, F.; Zimbalatti, G.; Proto, A.R. Pelletization of compost from different mixtures with the addition of exhausted extinguishing powders. *Agronomy* **2021**, *11*, 1357. [[CrossRef](#)]
73. Wang, C.; Guo, F.; Wu, S.; Fu, X.; Zhao, X.; Li, G. Effects and mechanisms of granulated compost on soil nitrogen supply and crop uptake: Preliminary evidence from a ¹⁵N tracing field experiment in tobacco. *Agronomy* **2025**, *15*, 2345. [[CrossRef](#)]
74. Shi, Y.; Ye, G.; Ao, G.; Wang, Z.; Liu, Y.; Sun, X.; Wang, K.; Yin, M.; Ling, H.; Sun, S. Humic acid enhances nitrogen retention in composting products by targeting denitrifying microbial communities and nitrogen metabolism genes. *Environ. Technol. Innov.* **2025**, *39*, 104335. [[CrossRef](#)]
75. Uddin, M.K.; Saha, B.K.; Wong, V.N.L.; Patti, A.F. Organo-mineral fertilizer to sustain soil health and crop yield for reducing environmental impact: A comprehensive review. *Eur. J. Agron.* **2025**, *162*, 127433. [[CrossRef](#)]
76. Nagarajan, A.; Chen, Y.; Raghavan, V.; Goyette, B.; Rajagopal, R. Sustainable nutrient recovery through struvite precipitation from poultry and multi-substrate agricultural waste digestates. *Bioresour. Technol. Rep.* **2024**, *27*, 101924. [[CrossRef](#)]
77. Kokulan, V.; Schneider, K.; Macrae, M.L.; Wilson, H. Struvite application to field corn decreases the risk of environmental phosphorus loss while maintaining crop yield. *Agric. Ecosyst. Environ.* **2024**, *366*, 108936. [[CrossRef](#)]
78. Misra, R.V.; Roy, R.N.; Hiraoka, H. *On-Farm Composting Methods*; FAO Land and Water Discussion Paper 2; Food and Agriculture Organization of the United Nations: Rome, Italy, 2003.

79. U.S. Environmental Protection Agency. *Types of Composting and Understanding the Process*; U.S. Environmental Protection Agency: Washington, DC, USA, 2016.
80. Onwosi, C.O.; Igbokwe, V.C.; Odimba, J.N.; Eke, I.E.; Nwankwoala, M.O.; Iroh, I.N.; Ezeogu, L.I. Composting technology in waste stabilization: On the methods, challenges and future prospects. *J. Environ. Manag.* **2017**, *190*, 140–157. [[CrossRef](#)] [[PubMed](#)]
81. Keng, Z.X.; Tan, J.J.M.; Phoon, B.L.; Khoo, C.C.; Khoiroh, I.; Chong, S.; Supramaniam, C.; Singh, A.; Pan, G.T. Aerated static pile composting for industrial biowastes: A systematic review. *Bioengineering* **2023**, *10*, 938. [[CrossRef](#)] [[PubMed](#)]
82. Yang, Y.; Chen, W.; Liu, G.; Cui, B.; Zhang, L.; Wuyun, D.; Wang, Q.; Wang, G.; Li, G.; Yuan, J. Effect of a semi-permeable membrane covered composting on greenhouse gas emissions and bacterial community succession: A comparative study with biomass materials covering. *J. Clean. Prod.* **2024**, *434*, 140146. [[CrossRef](#)]
83. Xiong, J.; Zhuo, Q.; Su, Y.; Qu, H.; He, X.; Han, L.; Huang, G. Nitrogen evolution during membrane-covered aerobic composting: Interconversion between nitrogen forms and migration pathways. *J. Environ. Manag.* **2023**, *345*, 118727. [[CrossRef](#)] [[PubMed](#)]
84. Sun, X.; Huang, G.; Huang, Y.; Fang, C.; He, X.; Zheng, Y. Large semi-membrane covered composting system improves the spatial homogeneity and efficiency of fermentation. *Int. J. Environ. Res. Public Health* **2022**, *19*, 15503. [[CrossRef](#)] [[PubMed](#)]
85. Fang, C.; Yin, H.; Han, L.; Ma, S.; He, X.; Huang, G. Effects of semi-permeable membrane covering coupled with intermittent aeration on gas emissions during aerobic composting from the solid fraction of dairy manure at industrial scale. *Waste Manag.* **2021**, *131*, 1–9. [[CrossRef](#)] [[PubMed](#)]
86. Climate Technology Centre and Network (CTCN). *Technology Fact Sheet: In-Vessel Composting*; Climate Technology Centre and Network (CTCN): Copenhagen, Denmark, 2011.
87. Xiong, J.; Su, Y.; He, X.; Han, L.; Huang, G. Effects of functional membrane coverings on carbon and nitrogen evolution during aerobic composting: Insight into the succession of bacterial and fungal communities. *Bioresour. Technol.* **2022**, *369*, 128463. [[CrossRef](#)] [[PubMed](#)]
88. Soto-Herranz, M.; Sánchez-Báscones, M.; Antolín-Rodríguez, J.M.; Martín-Ramos, P. Reduction of ammonia emissions from laying hen manure in a closed composting process using gas-permeable membrane technology. *Agronomy* **2021**, *11*, 2384. [[CrossRef](#)]
89. Li, R.; Cai, L.; Cao, J.; Wang, P.; Qu, H.; Chen, M.; Chen, Y. Effect of different multichannel ventilation methods on aerobic composting and vegetable waste gas emissions. *Environ. Sci. Pollut. Res.* **2023**, *30*, 112104–112116. [[CrossRef](#)] [[PubMed](#)]
90. Cordeiro, C.M.; Sindhøj, E.S. Situating the discourse of recycled nutrient fertilizers in circular economy principles for sustainable agriculture. *Front. Sustain.* **2024**, *5*, 1465752. [[CrossRef](#)]
91. Nordahl, S.L.; Preble, C.V.; Kirchstetter, T.W.; Scown, C.D. Greenhouse gas and air pollutant emissions from composting. *Environ. Sci. Technol.* **2023**, *57*, 2235–2247. [[CrossRef](#)] [[PubMed](#)]
92. Oviedo-Ocaña, E.R.; Abendroth, C.; Domínguez, I.C.; Sánchez, A.; Dornack, C. Life cycle assessment of biowaste and green waste composting systems: A review of applications and implementation challenges. *Waste Manag.* **2023**, *171*, 350–364. [[CrossRef](#)] [[PubMed](#)]
93. Teleshkan, E.; Van Schoubroeck, S.; Spiller, M.; Van Passel, S. Assessing policy impacts on nutrient circularity: A comprehensive review. *Nutr. Cycl. Agroecosyst.* **2024**, *129*, 337–351. [[CrossRef](#)]
94. Notice on Carrying Out the Pilot Program of Green Planting–Breeding Circular Agriculture. Available online: https://zzys.moa.gov.cn/gzdt/202105/t20210526_6368443.htm (accessed on 28 May 2026). (In Chinese)
95. Environmental Quality Incentives Program (EQIP). Available online: <https://www.nrcs.usda.gov/programs-initiatives/environmental-quality-incentives-program> (accessed on 28 May 2026).
96. Sustainable Use of Nutrients Under the Common Agricultural Policy. Available online: https://agriculture.ec.europa.eu/cap-my-country/sustainability/environmental-sustainability/low-input-farming/nutrients_en (accessed on 28 May 2026).
97. Liu, Y.; Tang, R.; Li, L.; Zheng, G.; Wang, J.; Wang, G.; Bao, Z.; Yin, Z.; Li, G.; Yuan, J. A global meta-analysis of greenhouse gas emissions and carbon and nitrogen losses during livestock manure composting: Influencing factors and mitigation strategies. *Sci. Total Environ.* **2023**, *885*, 163900. [[CrossRef](#)] [[PubMed](#)]
98. Sun, L.; Guan, W.; Tai, X.; Qi, W.; Zhang, Y.; Ma, Y.; Sun, X.; Lu, Y.; Lin, D. Research progress on microbial nitrogen conservation technology and mechanism of microorganisms in aerobic composting. *Microb. Ecol.* **2025**, *88*, 19. [[CrossRef](#)] [[PubMed](#)]
99. Temel, F.A.; Yolcu, O.C.; Turan, N.G. Artificial intelligence and machine learning approaches in composting process: A review. *Bioresour. Technol.* **2023**, *370*, 128539. [[CrossRef](#)] [[PubMed](#)]
100. Rosik, J.; Karczewski, M.; Stegenta-Dąbrowska, S. Optimizing the early-stage of composting process emissions: Artificial intelligence primary tests. *Sci. Rep.* **2024**, *14*, 27299. [[CrossRef](#)] [[PubMed](#)]
101. Lazrak, M.; Ait Baddi, G.; Achemchem, F.; Ayour, J.; Zaidouni, S.; Chebli, B. AI-driven and sensor-based composting in a connected bioreactor: A novel framework for predicting maturity and quality dynamics. *Waste Manag. Bull.* **2025**, *3*, 100254. [[CrossRef](#)]

102. Mu, D.; Horowitz, N.; Casey, M.; Jones, K. Environmental and economic analysis of an in-vessel food waste composting system at Kean University in the U.S. *Waste Manag.* **2017**, *59*, 476–486. [[CrossRef](#)] [[PubMed](#)]
103. Wang, H.; Qin, Y.; Xin, L.; Zhao, C.; Ma, Z.; Hu, J.; Wu, W. Preliminary techno-economic analysis of three typical decentralized composting technologies treating rural kitchen waste: A case study in China. *Front. Environ. Sci. Eng.* **2023**, *17*, 47. [[PubMed](#)]

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