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REVIEW

Research Progress on Microbial Nitrogen Conservation Technology and Mechanism of Microorganisms in Aerobic Composting

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Abstract
With economic development and improvements in living standards, the demand for livestock products has steadily increased, resulting in the generation of large amounts of livestock manure, which seriously pollutes the ecological environment and poses a threat to human health. High-temperature aerobic composting is an effective method for treating livestock manure; however, traditional composting processes often lead to considerable nitrogen loss, reduced efficiency of soil conditioners, and increased emissions of harmful gases. The incorporation of physical, chemical, and biological additives can effectively retain nitrogen within the compost. Among these, microbial agents are particularly noteworthy as they precisely regulate the microbial community structure associated with nitrogen transformation during aerobic composting, altering the abundance of functional genes and enzyme activities involved in nitrogen transformation. This approach significantly reduces nitrogen loss and harmful gas emissions. This paper reviews the application effects of microbial agents on nitrogen retention during aerobic composting and explores the underlying regulatory mechanisms, aiming to provide theoretical guidance and new research directions for the application of microbial agents in enhancing nitrogen retention during aerobic composting.

Keywords Aerobic composting · Nitrogen transformation · Microbial nitrogen retention technology · Regulatory mechanisms

Introduction

With rapid economic development and improvement in living standards, the demand for livestock products in China has been steadily increasing. According to data from the Ministry of Agriculture, as of 2021, the slaughter volumes of poultry, pigs, and cattle reached 15.74 billion, 671.28 million, and 47.07 million, respectively [1]. However, the livestock industry has produced a substantial amount of manure. The Ministry of Agriculture reports that China produces approximately 3.8 billion tons of livestock manure annually [2]. This manure is rich in nitrogen and phosphorus, and during storage, it releases ammonia (NH_3) and hydrogen sulfide (H_2S), both of which are odorous gases. The emission of these pollutants not only severely contaminates the ecological environment but also poses a threat to human health. Therefore, effectively treating livestock manure has become a crucial research topic in efforts to protect the environment and safeguard human health.

Aerobic composting is an efficient technological method for treating livestock manure. By conducting aerobic

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fermentation under high-temperature conditions, livestock manure is transformed into safe, stable, and nutrient-rich soil conditioners. This process not only significantly reduces the emissions of environmental pollutants from livestock manure but also effectively enhances composting efficiency, thereby improving soil quality and promoting sustainable agricultural development [3].

However, studies have demonstrated that the aerobic composting process leads to nitrogen losses accounting for 12–25% of the initial nitrogen content, with NH_3 volatilization losses representing 60–99% of this amount, along with a smaller portion of nitrous oxide (N_2O) emissions [4, 5]. This not only reduces the efficiency of composting but also contributes to air pollution. Regulating nitrogen transformation to mitigate NH_3 emissions during composting is a primary focus of nitrogen retention technologies in aerobic composting. The nitrogen loss during the composting process is influenced by factors such as the composition of raw materials, C/N ratio, and oxygen (O_2) concentration within the compost pile. The composition of compost materials (such as organic waste, discarded food, and crop residues) directly affects the microbial community structure and their metabolic activities. For example, materials rich in protein and nitrogen sources may promote microbial nitrogen assimilation and degradation activities [6]. The C/N ratio of compost plays a crucial role in nitrogen loss. When the C/N ratio is below 10 or above 30, nitrogen loss significantly increases. A lower C/N ratio leads to excessive mineralization of nitrogen, increasing nitrogen loss, while a higher C/N ratio directly results in nitrogen volatilization losses [7]. To optimize nitrogen conversion efficiency and reduce NH_3 loss, the optimal C/N ratio is between 24 and 30 [8]. Denitrifying microorganisms in compost prefer low-oxygen concentrations (< 0.2 mg/L) under low-oxygen conditions. Within the compost pile, the aggregation and compaction of materials usually limit oxygen penetration, and low O_2 concentrations are a major factor driving N_2O emissions [9]. Therefore, to reduce N_2O emissions, an appropriate aeration rate (e.g., 0.5 $L \cdot min^{-1} \cdot kg^{-1}$) should be maintained to ensure oxygen supply and suppress N_2O production [10]. An appropriate moisture content in compost also helps increase the porosity of the compost mixture, thereby increasing O_2 content, enhancing maturity, and reducing nitrogen loss [11].

The regulation of nitrogen transformation through physical, chemical, and biological pathways to reduce nitrogen loss during composting is a key area of focus for nitrogen conservation in aerobic composting. Physical and chemical additives such as zeolite, biochar, sulfur, and phosphoric acid can reduce NH_3 emissions in the short term [12–15], but they also have significant drawbacks. For instance, biochar, while adsorbing nitrogen, may also adsorb other essential nutrients (e.g., phosphorus and potassium), thus affecting the availability of other nutrients during composting [16]. The addition of zeolite may affect the diversity and metabolic activity of microorganisms, and its effectiveness in nitrogen retention is unstable due to uneven particle size and distribution [17]. Excessive use of sulfur and phosphoric acid can lower the soil pH (< 6.0), inhibiting the composting process and reducing compost quality. Long-term misuse may also disrupt the organic balance of the soil, negatively impacting plant growth [15]. In addition, the use of functional membranes can reduce NH_3 emissions by 7.34% and N_2O emissions by 26.27% [15], but the investment required for the assembly of such equipment is high [18], far exceeding the economic capacity of medium- and small-scale farms. In comparison, the use of nitrogen-retaining microbial agents (NRMA) does not require complex equipment or high-cost investments. It is simple to operate and suitable for composting processes of all scales. While other nitrogen conservation methods can slow down nitrogen volatilization, they cannot alter the nitrogen transformation pathway. However, NRMAs enhance microbial activity, allowing nitrogen to exist in a more stable and usable form, improving nitrogen utilization efficiency [19]. Moreover, NRMAs help increase the activity of beneficial microorganisms in compost, improve compost structure and fertilizing efficiency, and ensure soil health in agricultural fields [20]. They also have minimal negative environmental impact, avoiding additional pollution and soil pH imbalances introduced by chemical additives [21]. In conclusion, microbial nitrogen-conserving inoculants are flexible, efficient, and pollution-free, making them a promising method. Currently, mature products, such as MANURE PRO by LALLEMAND, are available globally [22]. However, there is still no clear explanation of the mechanisms behind the nitrogen-conserving action of these NRMAs which limits further development and optimization of these products.

Studies have shown that the addition of exogenous microorganisms not only promotes the maturity and quality of compost materials but also balances the succession of native microbial communities [23]. Adding NRMAs further improves nitrogen retention efficiency by enhancing nitrogen-related enzyme activities, thereby positively influencing nitrogen cycling and retention in the compost [24]. Consequently, the addition of NRMA represents a low-cost, highly efficient, and pollution-free nitrogen retention technology. However, the mechanisms underlying the effects of NRMA remain inadequately understood [25].

This paper will begin with an overview of the principles of nitrogen transformation during aerobic composting, review the nitrogen retention effects of NRMA as reported in existing studies, discuss the impact of NRMA on the microbial community in aerobic composting, analyze the regulatory mechanisms of nitrogen-related genes and enzyme activities, elucidate the nitrogen retention mechanisms, and propose future research directions. The aim is to provide theoretical support and technical guidance for the application of NRMA in nitrogen retention during aerobic composting.

Nitrogen Transformation Mechanism in Aerobic Composting

The nitrogen transformation process in aerobic composting primarily involves ammonification, nitrification, denitrification, and other nitrogen-related processes in composting.

Ammonification

Ammonification is the process by which microorganisms decompose organic nitrogen compounds to produce ammonia, representing the mineralization of organic nitrogen [26]. These microorganisms, aided by various enzymes, convert complex nitrogen-containing organic substances into simpler nitrogen-containing compounds, such as amino acids and peptides. Under the action of microbial deaminase, these compounds undergo deamination, resulting in the formation of NH_4^+–N or NH_3 [27]. Ammonium (NH_4^+) can be converted into NH_3 under alkaline conditions, leading to its volatilization into the atmosphere [28, 29]. Furthermore, NH_4^+–N is highly soluble in water and can leach into the soil through leachate [30]. Consequently, ammonification contributes to nitrogen loss by transforming organic nitrogen into ammonia during composting, which negatively impacts nitrogen retention efficiency.

Nitrification

Nitrification occurs under aerobic conditions, where NH_4^+ serves as a substrate and is oxidized to hydroxylamine (NH_2OH) by ammonia monooxygenase (AMO). Subsequently, hydroxylamine is further oxidized to nitrite (NO_2^-) by hydroxylamine oxidoreductase (HAO). NO_2^- is then converted to nitrate (NO_3^-) under the action of NO_2^- oxidoreductase [31]. This process is completed through a three-step oxidation reaction. Nitrification, primarily carried out by nitrifying bacteria, mainly occurs during the heating and cooling phases of composting at temperatures below 40–55 °C [32, 33]. Throughout the composting process, nitrification transforms NH_4^+ to NO_3^-, preventing the conversion of NH_4^+ to NH_3 and thereby reducing nitrogen loss [31].

Denitrification

Denitrification is the process by which NO_3^- or NO_2^- is reduced to nitrogen (N_2). This process is facilitated by the synergistic action of complex enzyme systems, including nitrate reductase, nitrite reductase, nitric oxide reductase, and N_2O reductase [34]. Nitrate nitrogen (NO_3^--N) is gradually reduced to nitrite nitrogen (NO_2^--N), nitric oxide (NO), N_2O, and ultimately nitrogen gas (N_2) [34]. This process typically occurs in compost that is deficient in oxygen, which can result from factors such as high moisture content, low porosity, or inadequate aeration [34]. Denitrification can lead to a relatively small loss of nitrogen in the compost, estimated at approximately 5% [35].

Other Nitrogen Transformation Processes Related to Composting

Ammonium assimilation involves the conversion of NH_4^+ into organic nitrogen through the coordinated action of glutamate dehydrogenase, glutamine synthetase, and glutamate synthetase [36]. This process significantly reduces nitrogen loss during composting, enhances nitrogen retention in the compost, and improves the soil conditioner efficiency of the compost [37]. A small amount of nitrogen-fixing bacteria present in the compost can convert limited amounts of atmospheric nitrogen or nitrogen produced from denitrification into NH_4^+, contributing to nitrogen retention [38].

In summary, nitrogen loss during aerobic composting primarily occurs through NH_3 volatilization, NH_4^+-N leachate leaching, and incomplete denitrification, such as NO, N_2O, and N_2 emission [39]. The addition of NRMA to aerobic composting can enhance the nitrification process by introducing nitrifying bacteria, which promote the conversion of NH_4^+-N into NO_3^--N. Simultaneously, the ammonifying bacteria present in these NRMA effectively facilitate ammonium assimilation, converting NH_4^+-N into amino acids and other nitrogen-containing organic compounds. This process not only reduces the volatilization loss of NH_4^+-N but also increases the nitrogen content in the compost, thereby improving the efficiency of nitrogen utilization [40, 41].

Microbial Additives, Their Effects on Nitrogen Retention, Environmental Benefits, and Trade-offs

Microbial additives can consist of a single strain or a composite agent composed of several different microorganisms [42, 43]. Previous studies have investigated various NRMAs for aerobic composting, The primary types of NRMA employed include *Bacillus*, ammonia-oxidizing bacteria, cellulose-degrading bacteria, nitrifying bacteria, and nitrogen-fixing rhizobia [35, 42–45]. The microbial communities with outstanding performance are summarized as follows: The use of *Bacillus megaspora*, *Thiobacillus* sp., *Saccharomyces exiguus*, or *Bacillus licheniformis* individually can effectively reduce NH_3 emissions from livestock manure, reduction of odor emissions by 31.3–90% [46–49]. Strains of the *Geobacillus* have been shown to reduce N_2O emissions by 89.3% [50]. The synergistic application of different strains to construct a composite microbial consortium has further enhanced nitrogen retention efficiency. For instance, the addition of a chicken manure-integrated microbial consortium increased the total nitrogen content by approximately 28.3% while simultaneously reducing NH_3 and N_2O emissions [51]. In cow manure substrates, adding ammonia-oxidizing microbial consortia increased the total Kjeldahl nitrogen content by 24.43–38.87% [19]. When *Bacillus subtilis*, *Bacillus licheniformis*, *Trichoderma viride*, and *Aspergillus niger* were added to cow manure at proportions of 0.1–0.4%, the total nitrogen content increased by 5.5–20.6% [52]. In pig manure, the addition of a composite microbial consortium composed of *Bacillus subtilis* sp. NF1 and other strains increased the total nitrogen content by up to 55.35% [53]. The types of nitrogen-retaining microbial agents (NRMAs) utilized and their effects on nitrogen retention are summarized in Table 1. Studies have shown that the addition of microbial inoculants during aerobic composting significantly enhances compost maturity while reducing odor emissions and nitrogen losses. Consequently, various mature NRMA products are now available in the market, such as MANURE PRO by LALLEMAND, livestock manure fermentation inoculant VT1010 (Beijing VOTO Biotech Co., Ltd.), and deodorant VT400 (Beijing VOTO Biotech Co., Ltd.).

In addition, based on economic analysis and life cycle assessment (LCA), the ratio of ecological efficiency, economic benefits, and potential environmental impacts of improved technology applications has become an important indicator for measuring the integrated economic and environmental impacts [69]. Research on the microbial inoculation technology for nitrogen conservation in composting, assessed through LCA and/or techno-economic studies, has not been reported. Therefore, this study attempts to elucidate the process through the aerobic composting technology itself. The organic matter and nutrients, such as nitrogen and phosphorus, in the matured compost are essential for crop growth. However, the production of nitrogen and phosphorus fertilizers requires land use, depleting mineral resources while consuming large amounts of energy. Studies have shown that the land-use impact of producing 1 kg of nitrogen fertilizer is 0.31 m^2 per crop equivalent [70, 71]. In terms of mineral resource scarcity, according to the Ecoinvent database, the production of 1 kg of nitrogen fertilizer results in 0.027 kg of copper equivalent [70]. The energy demand for nitrogen fertilizer production is high, as it requires high process temperatures and pressures, accounting for 90% of the total energy needed for fertilizer production [72, 73]. Although the actual substitution rate of compost for chemical fertilizers across different regions is still difficult to quantify and involves considerable uncertainty, numerous studies suggest that applying organic fertilizers derived from composting to agricultural soils can partially replace chemical fertilizers, significantly reducing the resource consumption in fertilizer production, while improving soil organic matter content [74]. This directly increases soil carbon sequestration and improves the carbon footprint of the system [70] while indirectly improving soil ecology, such as moisture retention, crop productivity, and nutrient cycling [75]. A life cycle assessment also found that more advanced composting technologies, such as reactor composting, improved environmental benefits and ecological efficiency [76]. Besides the positive environmental effects of compost use in agriculture, methane and nitrous oxide emissions from aerobic composting significantly contribute to global warming [70]. Phong surveyed the impact of industrial composting on global warming, finding that the impact of composting 1 kg of biowaste on global warming was 0.118 kg CO_2 equivalent per kg of biowaste [77]. Therefore, research on emission reduction measures for the aerobic composting process is urgently needed. The microbial inoculation technology reviewed in this paper is one such promising emission reduction measure, which also promotes the maturation process and enhances the biosafety of composting [78].

Mechanisms of Microbial Agents Affecting Nitrogen Transformation in Composting

Regulation of Nitrogen-Transforming Microbial Abundance

During aerobic composting, nitrogen exists in various forms, including NH_4^+-N, NO_3^--N, and organic nitrogen. The transformation of these nitrogen forms relies heavily on the activities of diverse microorganisms, such as ammonifying bacteria, nitrate-reducing bacteria, nitrifying bacteria, nitrogen-fixing bacteria, and other functional microorganisms [79]. *Sphingobacterium*, a nitrifying bacterium, is frequently observed in composting and plays a crucial role in the conversion of ammonia to NO_3^- and NO_2^- [24]. *Sporosarcina* is an efficient nitrogen-fixing bacterium, and its metabolic processes are essential for nitrogen formation and retention during composting, which is critical for compost quality and fertility [80].

Previous studies have demonstrated that inoculating aerobic composting with ammonia-oxidizing bacteria (AOB) as NRMA significantly impacts the microbial community and its functions within the compost [19]. AOB inoculation enhances the growth of *Bacillus*, which is particularly active during the high-temperature phase of composting. The abundance increased to 29.18%, resulting in a reduction

Table 1 Nitrogen retention effect of different NRMA on aerobic compost

Types of microbial agents	Pile matrix	Amount of addition (fresh weight%)	Nitrogen-retaining effect (%) Compared to the control group					References
			NH_3	N_2O	NO_2^--N	NO_3^--N	TN and TKN	
Bacillus strain sp. TAT105	Pig manure	2.38					TN↑22	[42]
Ammonia-oxidizing bacteria sp. AOB	Chicken manure; rice straw	5	↓88		↑44.5		TN↑1.08	[43]
Microbial agents screened in pig farm wastewater and leaf litter soil	Pig manure; straw and mushroom waste; sawdust and rice husk	0.8	↓25.52					[54]
Bacillus subtilis, *Bacillus licheniformis*	Food waste	0.9		↓17–54				[55]
Cellulose-degrading bacteria sp. WSD.5	Chicken manure	5	↓25.9	↓34.98				[35]
Bacillus megaspora sp. 1.1870	Pig manure	5	↓31.34	↓53.16				[47]
Cellulose-degrading bacteria sp.	Cattle manure	0.3		↓45				[56]
Thiobacillus sp. 1904	Chicken manure	5	↓61.5			↑33.5	TN↑28.20	[48]
Denitrifying and ammonia bacteria sp.	Sludge	0.35			↑28.85	↑33.13	TKN ↑4.94%	[44]
Medium-temperature fungus-F1, medium-temperature bacteria-Z1, high-temperature bacteria-Z2 and their combination	Cattle manure	5	↓8.45–23.29	↓22.85–61.13			TKN ↑13.48–19.60	[57]
Ammonia oxidizing bacteria high temperature resistant strain sp. T-AOB-2, medium temperature strain sp. M-AOB-4 and compound microbial agent sp. MT-AOB-2–4 formed by compound bacteria	Cattle manure	5	↓29.98–46.94		↑21.85–38.90	↑33.90–41.79	TKN ↑24.43–38.87	[19]
Bacillus subtilis sp. NF1, *thermophilic bacteria* sp. NF2, and *combined addition* sp. NF3	Cow manure	5	↓12.77–25.11	↓23.01–42.75		↑8.96–19.40	TKN ↑38.43–55.35	[46]
Carbon-based microbial agents CBMA	Chicken manure	10	↓25.06			↑36.59	TN ↑35.02	[31]
Azotobacter chroococcum (GCA_016406165.1), *Bacillus subtilis* (GCA_023612315.1), *Saccharomonospora* sp. (GCA_015910535.1), *Streptomyces albidoflavus* (GCA_019286195.1)	Food waste	5					TN ↑20.6	[58]
Acinetobacter radioresistens strain sp. GH16093 (HA-1) and *Bacillus nitratireducens strain Bnit1* sp. HA-2	Cattle manure	5	↓36.1	↓32.1			TN ↑15.1	[32]
Thermophilic nitrifying bacteria sp.	Sewage sludge	5	↓29.7				TN ↑10.58	[33]
Chicken manure integrated microbial consortium (CMMC)	Chicken manure	10	↓21.8	↓44.5				[51]
Thiobacillus thioparus sp. 1904	Chicken manure	5	↓21.86	↓31.84			TN ↑28.3	[59]
Pichia membranifaciens	Pig manure	1					TN ↑4.79–29.61	[60]
Bacillus subtilis, *Bacillus* licheniformis, green wood mold, *Aspergillus niger*	Cow manure	0.1–0.4					TN ↑5.5–20.6	[52]
Bacillus sphaericus DF-2	Pig manure	0.3	↓65				TN ↑30	[61]
Bacillus subtilis CGMCC No 0.19516	Chicken manure	1	↓76.64			↑220		[62]

Table 1 (continued)

Types of microbial agents	Pile matrix	Amount of addition (fresh weight%)	Nitrogen-retaining effect (%) Compared to the control group					References
			NH_3	N_2O	NO_2^--N	NO_3^--N	TN and TKN	
Streptomyces etiolaris, *Bacillus subtilis*, *Lactobacillus acidophilus*, *Clostridium perfringens*, *Aeromonas pyogenes*, *Vibrio fibrosus*	Cow manure	10–20						[63]
Nitrate nitrogen assimilating bacteria	Clay powder	10–200				↑40–70		[64]
Multi-crustal layer thermophilic complex			↓60					[65]
Nitrobacillus harbinensis BM62	Cow manure	10	↓6.2–36.7		18.1		TN ↑9.2	[66]
Streptomyces fines, *Bacillus subtilis*, *Pseudomonas aeruginosa*, *Nitrobacter*, *Denitrifying bacteria*	Mixture of Cow manure, pig manure, chicken manure	0.1–0.2	↓64				TN ↑35	[67]
Geobacillus thermodenitrificans, *Geobacillus stearothermophilus*, *Geobacillus kaustophilus*, *Geobacillus subterranens*, *Geobacillus thermoleovorans*, *Geobacillus caldoxylosilyticas*		20	During the composting treatment with *Geobacillus* microorganisms, N_2O concentrations were significantly lower than in the control. At the sixth week of treatment, the concentration of N_2O in the compost with *Geobacillus* microorganisms was reduced to approximately 0.3 ppm, compared to 2.8 ppm in the control group, suggesting that the use of the microorganisms was effective in suppressing the emission of the greenhouse gas N_2O					[52]
Saccharomyces exiguus SJP6728AF1 (KCCM-10675P), *Saccharomyces exiguus* SJP6729AF2 (KCCM-10677P) et al		0.1–1	50–90					[49]
Bacillus licheniformis MM76 and MM172			*Bacillus licheniformis* strains in the bacterial compositions are able to assimilate ammonia efficiently, which helps to reduce ammonia volatilization losses during the composting process and at the same time provides an available source of nitrogen for plants or mushrooms					[50]
Sphingopyxis terrae subsp. *terrae* YC-JH3, *Methylomonas methanica* R-45371, *Pseudoxanthomonas mexicana* GTZY *Methylosinus trichosporium* OB3b, *Hyphomicrobium zavarzinii* ATCC 27496ZV-62			Bacteria in the compositions are capable of fixing nitrogen at rates in excess of 2.0 µmol/gDW/day, with a maximum nitrogen fixation rate of 2.5 µmol/gDW/day					[68]

This table includes the following nitrogen compounds, ammonia (NH_3), nitrous oxide (N_2O), nitrite nitrogen (NO_2^--N), nitrate nitrogen (NO_3^--N), total nitrogen (TN), and total Kjeldahl nitrogen (TKN); ↓ indicates a reduction in gas emissions, and ↑ indicates an increase in nitrogen-related forms of nitrogen loss rate to 24.16%; at the high-temperature stage of composting, the number of operational taxonomic units (otus) analyzed by sequencing of 16S rRNA gene amplicons was 57 in the control group, whereas the number of otus in the treatment group with the microbial additive MT-AOB-2–4 increased significantly to 313, an increase of 256 otus compared to the control group [19]. Moreover, inoculation with heat-tolerant ammonia-oxidizing bacteria AOB increased the abundance of Bacillaceae in the bacillus group to 29.18% during the high-temperature phase and reduced the nitrogen loss rate to 24.16% [19]. This suggests that inoculation greatly increased bacterial abundance and microbial diversity during the high-temperature stage. This increase may be attributed to the presence of *Bacillus* in the AOB inoculant, which is relatively heat-tolerant and thus highly active during composting. *Bacillus* has been recognized as a key genus in regulating nitrogen transformation, playing a crucial role in nitrogen retention and transformation. Pan influence microbial abundance and metabolic activity, thereby helping to reduce nitrogen loss and improve nitrogen retention efficiency [19, 43, 81, 82].

In addition to regulating nitrogen transformation, NRMAs enhance the growth environment for nitrogen-transforming microorganisms. Zhong et al. found that the addition of NRMA during aerobic composting can significantly enhance nitrogen utilization efficiency. The primary mechanism underlying this improvement is the increased abundance of microorganisms involved in nitrogen transformation, which promotes effective nitrogen conversion. Research indicates that NRMA contains ammonifying bacteria, nitrifying bacteria, nitrite-oxidizing bacteria, and nitrogen-fixing bacteria [83]. These microorganisms effectively mitigate ammonia generation and nitrogen loss by facilitating the nitrification of ammonia and the subsequent conversion of nitrite [83]. For example, the addition of the microbial agent NRMA significantly increased the abundance of nitrogen-transforming bacteria such as *Paucisalibacillus*, *Sporosarcina*, *Sphingobacterium*, and *Oceanobacillus*, especially during the high-temperature phase. Their relative abundances increased by 7.2%, 8.33%, 0.18%, and 0.01%, respectively, resulting in a 58.8% reduction in nitrogen loss and a 22.6% increase in total nitrogen content [83]. This finding suggests that the addition of the microbial agent enhanced the activity of these microbial communities, thereby reducing ammonia emissions and improving nitrogen utilization efficiency [84].

The study conducted by Liu et al. demonstrates that the incorporation of NRMA HA-1 and HA-2 significantly elevates the NO_3^--N content in compost [45]. After inoculating with microbial agents HA-1 and HA-2, the relative abundance of *Proteobacteria* in the bacterial agent group increased by 32.3%, and the abundance of *Firmicutes* was higher, promoting nitrification and reducing nitrogen loss; the cumulative NH_3 and N_2O emissions in the bacterial agent group were 36.1% and 32.1% lower, respectively, compared to the control group [45].

Consequently, the addition of different microbial inoculants during aerobic composting significantly increased the abundance of nitrogen-transforming microbial communities (such as *Bacillaceae*, *Proteobacteria*, *Firmicutes*, *Paucisalibacillus*, *Sporosarcina*, *Sphingobacterium*, and *Oceanobacillus*) and altered the composition of these communities, thereby reducing nitrogen losses (such as NH_3 and N_2O emissions) and enhancing nitrogen retention. The total nitrogen content and compost quality were also improved.

Changes in Nitrogen-Transforming Enzyme Activity

The nitrogen cycle during aerobic composting involves several key enzymes, each playing a crucial role in the transformation of nitrogen compounds. For instance, urease catalyzes the hydrolysis of urea, converting it into ammonia, which is subsequently transformed into ammonium ions [58]. AMO is a vital enzyme found in AOB and ammonia-oxidizing archaea (AOA) and responsible for oxidizing ammonia into NO_2^-, a critical step in the conversion of nitrogen from organic to inorganic forms. Nitrite oxidase then oxidizes NO_2^- into NO_3^-, stabilizing nitrogen in an oxidized form for effective utilization. Nitrate reductase plays an essential role in nitrogen reduction by converting NO_3^--N to NO_2^--N under anaerobic conditions. Nitrite reductase further reduces NO_2^- to NH_3, completing the nitrogen reduction process. Nitrous oxide reductase is involved in the reduction of N_2O during the denitrification process. Additionally, nitrogenase is crucial for nitrogen fixation, converting nitrogen gas into usable nitrogen compounds during aerobic composting [85].

NRMAs significantly influence enzyme activities. The addition of these agents can regulate enzyme functions through various mechanisms, including the adjustment of compost temperature and pH, acting as enzyme activators or inhibitors, and optimizing the nitrogen cycle, thereby enhancing nitrogen utilization efficiency [58]. It was shown that the inoculation of cold-adapted microbial agent (CAMA) significantly increased the urease activity during aerobic composting of chicken manure and sawdust, with a peak urease activity of 7.82 mg NH_4^+-N g^{-1}24 h^{-1} in the treatment group inoculated with CAMA, while that of the control group was only 6.24 mg NH_4^+-N g^{-1} 24 h^{-1} [86]. Throughout the composting process, the urease activity of the control group was consistently lower than that of the agent-added group, indicating that the addition of CAMA accelerated the decomposition of urea and its conversion into NH_4^+-N. During the whole composting process, the urease activity of the control group was always lower than that of the group with the addition of bacteriophage, which indicated that the addition of CAMA accelerated the decomposition of urea and converted it into NH_4^+-N, which effectively improved the efficiency of nitrogen retention [86].

Moreover, in the process of aerobic composting, the addition of NRMA significantly influences the activity of enzymes involved in nitrogen transformation. The nitrogen-fixing microorganisms present in these agents, such as *Rhizobium* and Actinobacteria, effectively convert atmospheric nitrogen into ammonia, which is accessible to plants. In the composting environment, when these nitrogen-fixing microorganisms are provided with optimal growth conditions, they regulate the synthesis and activation of nitrogen-transforming enzymes by secreting specific signaling molecules [43]. The upregulation of the expression of these key enzymes not only enhances the efficiency of nitrogen fixation but also promotes the transformation of ammonia, thereby facilitating the accumulation of organic nitrogen in the compost [87]. Previous studies have reported that the addition of *Thiobacillus* 1904 during the aerobic composting of chicken manure and mushroom residue significantly elevated compost temperatures ($P < 0.01$) [48]. The expression of AMO was suppressed as temperatures increased, particularly during the late high-temperature and maturation phases ($P < 0.01$). This phenomenon reduces NH_3 volatilization losses, thereby benefiting nitrogen transformation and retention. Concurrently, nitrite oxidoreductase (NXR) activity exhibited a negative correlation with temperature fluctuations. In this study, the expression of NXR gene in the high-temperature and maturation stages of compost was significantly higher in the group treated with *Thiobacillus* 1904 microbial agent than in the control group ($P < 0.01$) [48]. The oxidation of nitrite to nitrate was catalyzed by NRX [88, 89]. So, the addition of *Thiobacillus* 1904 microbial agent promoted the conversion of NO_2^- to NO_3^-, which resulted in a significantly higher NO_3^--N content in the treatment group than in the control group at the end of the composting process. Thus, NRMA optimized nitrogen conversion and increased nitrogen retention capacity by modulating the activities of AMO and NXR.

Changes in the Abundance of Functional Genes

Nitrogen transformation during aerobic composting is a complex biochemical process that involves multiple microbial functional genes, including *amoA*, *napA*, *napB*, *nif*, *hao* [45, 54, 90, 91]. During aerobic composting, the *amoA* gene encodes the alpha subunit of AMO, a crucial enzyme involved in ammonia oxidation. Ammonia-oxidizing bacteria convert (NH_4^+-N) into NH_2OH through the action of AMO. The expression of the *amoA* gene can mitigate ammonia volatilization, thereby reducing nitrogen loss during the composting process [54]. Liu et al. discovered that the addition of NRMAs associated with nitrogen transformation significantly enhanced the expression of the *amoA* gene in the aerobic composting of pig manure mixed with sawdust and rice husks. This enhancement facilitated the conversion of ammonia into nitrogen compounds, decreased NH_3 volatilization, and improved nitrogen retention in the compost [54].

The *napA* and *napB* genes encode the alpha and beta subunits of nitrate reductase, which catalyzes the reduction of nitrate. Liu et al. inoculated NRMA consisting of *Acinetobacter* strain GH16093 (HA-1) and *Bacillus* sp. strain Bnit1 (HA-2) in different combinations during aerobic composting. Three groups of bacteriological treatments were formed [45]. In this study, using metagenomics analysis, the expression of napA and napB genes was reduced by up to 56.6% in the fungicide-treated group as compared to the control group, suggesting that inoculation with NRMA inhibited the expression of *napA* and *napB*. The inhibition of nitrate reduction contributed to the retention of more NO_3^--N in the compost, thereby improving nitrogen retention and the overall quality of the compost [45].

The *nif* gene encodes nitrogenase, an enzyme responsible for reducing nitrogen gas (N_2) into NH_3, thereby facilitating nitrogen fixation [26]. Previous studies on the aerobic composting of cattle manure and straw demonstrated that the addition of NRMA HA-1 and HA-2 suppressed the expression of the *nif* gene compared to the control group, leading to a reduction in ammonia production during biological nitrogen fixation. This suppression resulted in decreased NH_3 volatilization and nitrogen loss [45]. By more effectively regulating ammonia generation and transformation, nitrogen retention efficiency was enhanced [90].

The *hao* gene encodes HAO, an enzyme that catalyzes the oxidation of NH_3 into NO_2^-, which is subsequently converted into NO_3^- [70]. This process is a crucial component of the nitrogen cycle, facilitating nitrogen transformation and mineralization and enhancing the quality and maturity of compost [92]. Although the expression level of the *hao* gene is relatively low compared to other functional genes, studies have demonstrated that inoculating with NRMA can increase *hao* gene expression, thereby promoting nitrification during the aerobic composting process [45]. This enhancement facilitates the accumulation of NO_3^--N, reduces NH_3 emissions, and ultimately achieves nitrogen retention during aerobic composting, leading to improved compost quality.

The *nxrA* gene encodes nitrate reductase, and variations in the expression of this gene can influence the conversion rate of NO_2^- to NO_3^-, thereby affecting nitrogen transformation and release [48]. Lu et al. discovered that during the high-temperature and maturation stages of composting, the expression of the *nxrA* gene in the microbial agent treatment groups (T3: 0.25% sulfur + 5% *Thiobacillus* 1904, and T4: 5% *Thiobacillus* 1904) was significantly higher than that in the control group ($P < 0.01$) [48]. At the end of composting, the NO_3^--N content of the treatment group with added fungicide was significantly increased by 156.58% compared to the control group [48]. This finding suggests that the addition of NRMA likely enhanced the expression of the *nxrA* gene, thereby increasing nitrate production efficiency and NO_3^--N content, effectively fixing nitrogen and reducing nitrogen volatilization and loss. The mechanism of *Thiobacillus* 1904 in regulating the nitrogen transformation process during aerobic composting is shown as follows (Fig. 1).

The *nirK*, *nirS*, *nirB*, and *norC* genes encode nitrite reductases, which facilitate the conversion of NO_2^--N into N_2O during aerobic composting. Zhou et al. discovered that the addition of a microbial nitrogen-retaining agent composed of *Anoxybacillus*, *Paenibacillus*, and *Geobacillus* significantly influenced nitrogen transformation during the composting process [93]. The results showed that the abundance of nirK gene in the NRMA group formed by inoculation of *Anoxybacillus*, *Paenibacillus*, and *Geobacillus* complex was consistently lower than that of the control group throughout the composting cycle, which effectively suppressed denitrification and reduced the volatilization of nitrogen in the form of N_2O and N_2. This improved the retention of nitrogen [93]. Guo et al. also confirmed that the use of NRMA decreased *nirK* gene abundance, thereby inhibiting the conversion of NO to N_2O, significantly reducing greenhouse gas (NO_X) emissions from composting and enhancing nitrogen retention efficiency [94]. In the aerobic composting of cattle manure, the addition of a microbial nitrogen-retaining agent composed of *Acinetobacter* strain GH16093 (HA-1) and *Bacillus* strain Bnit1 (HA-2) significantly reduced the expression levels of the *nirS*, *nirB*, and *norC* genes, thereby inhibiting N_2O emissions compared to the control group [32].

In conclusion, nitrogen transformation during aerobic composting is a complex biochemical process regulated by various microbial functional genes, primarily *amoA*, *napA*, *napB*, *nif, hao*, *nirK*, *nirS*, *nirB*, *norC*, and *nxrA*. Studying the regulation and abundance of these genes provides valuable insights into the mechanisms of microbial involvement in nitrogen transformation. The addition of NRMA enhances the expression of *hao*, *amoA*, and *nxrA*, which increases ammonia oxidation and reduces NH_3 volatilization. Furthermore, these agents inhibit the expressions of *napA*, *napB*, *nirK*, *nirS*, *nirB*, and *norC*, thereby decreasing nitrate reduction and N_2O emissions, while simultaneously promoting the expression of the *nif* gene, which aids in nitrogen fixation [45, 54, 93–95]. As a commonly used microbial additive *Bacillus sphaericus* in the nitrogen conservation process of aerobic composting, its regulation mechanism of nitrogen transformation process in aerobic composting is as follows (Fig. 2). Consequently, the incorporation of NRMA increases NO_3^--N content and improves nitrogen retention efficiency in aerobic composting.

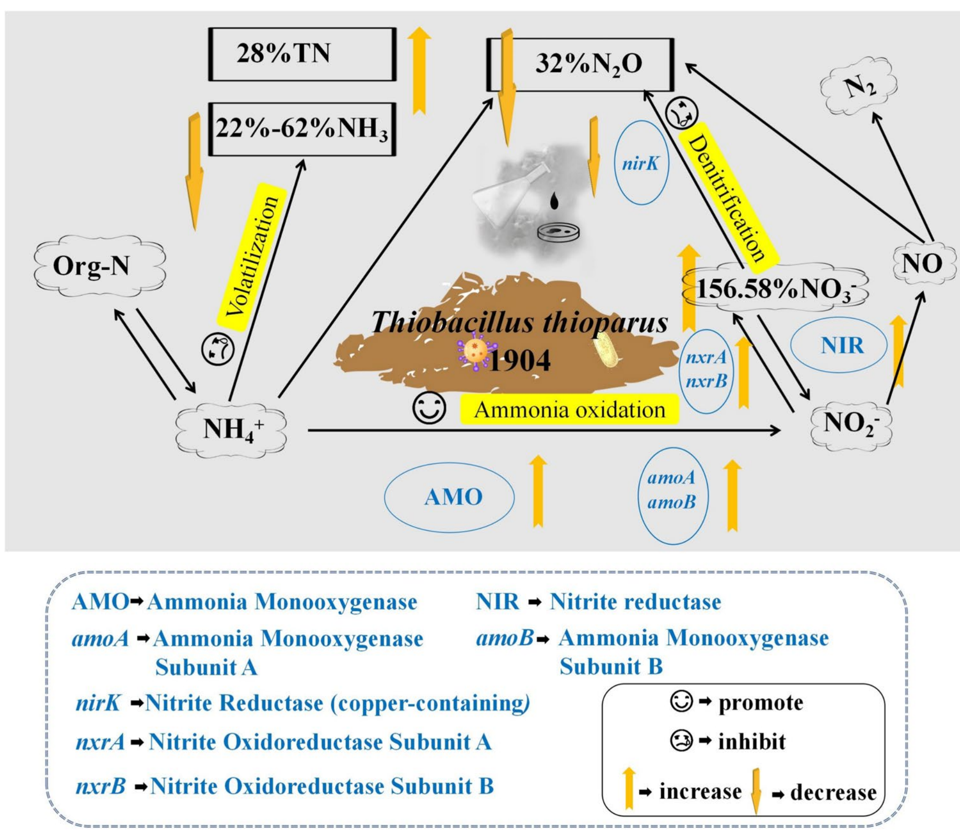

Fig. 1 Mechanism of nitrogen loss reduction in composting by *Thiobacillus thioparus* 1904

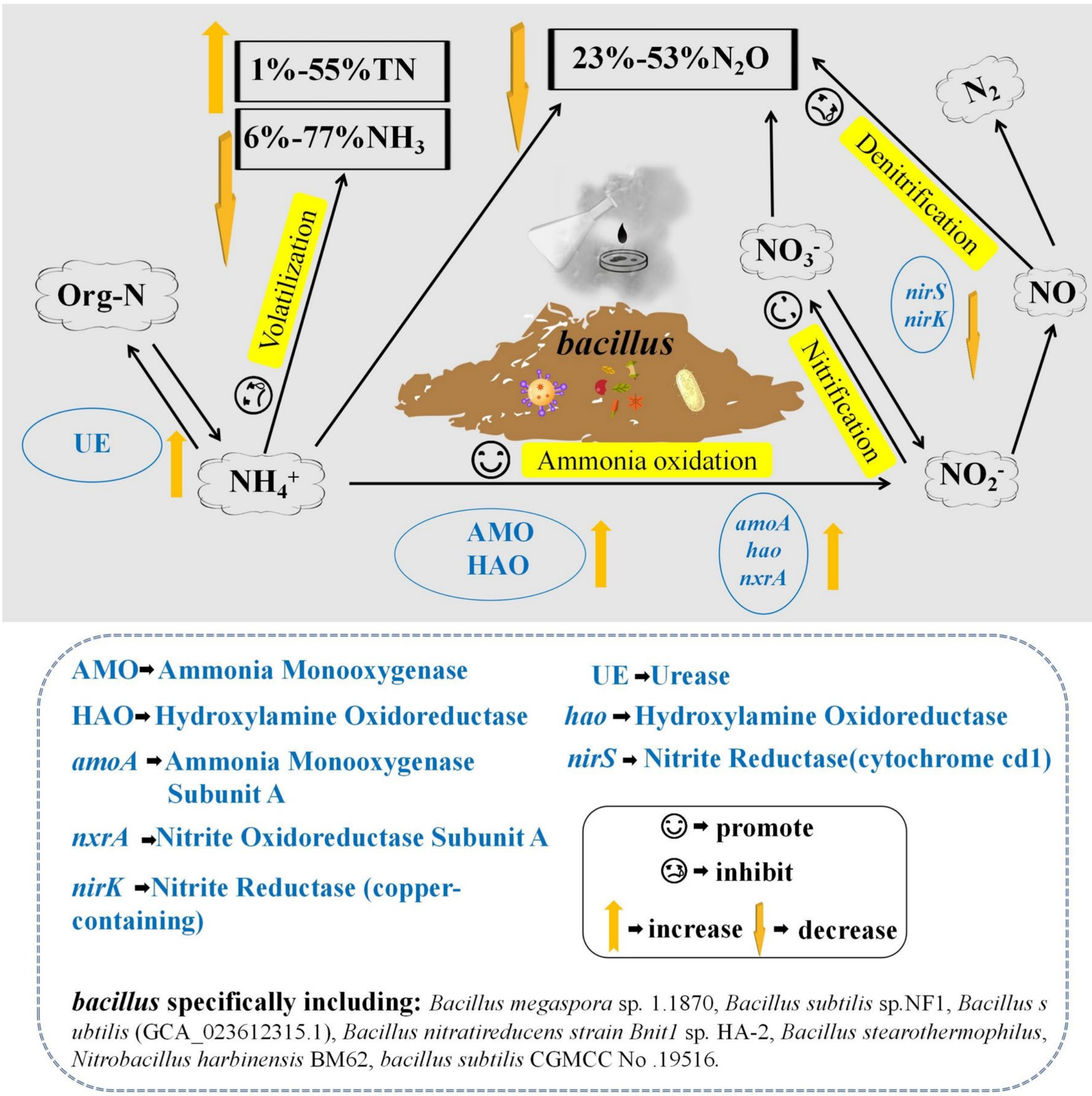

Fig. 2 Mechanism of nitrogen loss reduction in composting by *Bacillus*

Conclusion and Recommendations for Future Study

Aerobic composting is an effective method for the safe and efficient management of livestock manure. Microbial nitrogen-retaining technology involves the addition of microbial agents to aerobic composting, which helps regulate microbial abundance, enzyme activity, and gene expression related to nitrogen transformation, thereby achieving nitrogen retention. The regulation of nitrogen-transforming microorganisms primarily focuses on genera such as *Bacillus* and *Acinetobacter*. The incorporation of NRMA can enhance their abundance, influence nitrogen transformation processes, and increase the accumulation of NO_3^--N in compost, with a positive correlation observed between microbial abundance and NO_3^--N content. Furthermore, the addition of these agents modifies the expression of functional genes associated with nitrogen transformation, promoting the expression of *amoA*, *nxrA*, and *hao* genes while inhibiting the expression of *napA*, *napB*, *nirK*, *nirS*, *nirB*, and *norC* genes. This modulation affects enzyme activity, regulates nitrogen transformation pathways and rates, optimizes nitrogen retention and utilization efficiency in compost, and achieves low-cost, high-efficiency nitrogen retention in the aerobic composting of livestock manure.

Future research on microbial nitrogen-retaining technologies in aerobic composting of livestock manure could provide new insights for researchers in the following directions:

1. Although the addition of NRMA helps reduce NH_3 emissions, its effect on the reduction of N_2O emissions, which have a strong greenhouse effect, is often not significant and may even increase. To address this issue, enhancing specific microbial communities or adding specific enzyme preparations to achieve synergistic reduction of both ammonia and nitrous oxide can further improve the environmental benefits of composting
2. Assessing the environmental impacts of microbial nitrogen-retaining technologies in long-term compost management, including potential benefits in terms of long-term nitrogen loss, soil improvement, and carbon sequestration. Long-term assessments should ensure the sustainability and long-term benefits of microbial nitrogen-retaining technologies
3. Considering factors such as climate change, soil characteristics, and agricultural production needs, developing more comprehensive composting management systems that not only enhance nitrogen retention efficiency but also promote soil health and improve ecological benefits for farmland

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Data Availability No datasets were generated or analysed during the current study.

Declarations

Competing Interests The authors declare no competing interests.

References

1. National Bureau of Statistics of China (2023) China rural statistical yearbook. Beijing: China Statistics Press
2. Zai X (2016) Interpretation of the plan on promoting the pilot site of agricultural waste resource utilization. Comprehensive Util Resources China 34(10):15–16
3. Zheng G, Yu B, Wang Y, Ma C, Chen T (2020) Removal of triclosan during wastewater treatment process and sewage sludge composting-a case study in the middle reaches of the Yellow River. Environ Int 134:105300. https://doi.org/10.1016/j.envint.2019.105300
4. Nordahl SL, Preble CV, Kirchstetter TW, Scown CD (2023) Greenhouse gas and air pollutant emissions from composting. Environ Sci Technol 57(6):2235–2247
5. Zhang J, Wang Y, Yu D, Tong J, Chen M, Sui Q, ChuLu B, Wei Y (2017) Who contributes more to N_2O emission during sludge bio-drying with two different aeration strategies, nitrifiers or denitrifiers? Appl Microbiol Biotechnol 101(8):3393–3404
6. Li X, Wang S, Sun Z, Wang S, Shuai W, Shen C et al (2021) Performance and microbial community dynamics during rice straw composting using urea or protein hydrolysate as a nitrogen source: a comparative study. Waste Manag 135:130–139. https://doi.org/10.1016/j.wasman.2021.08.02
7. Zhou J (2017) The effect of different C/N ratios on the composting of pig manure and edible fungus residue with rice bran. Compost Sci Utilizat 25(2):120–129
8. Liu Q, Liu B, Zhang Y, Hu T, Lin Z, Liu G et al (2019) Biochar application as a tool to decrease soil nitrogen losses (NH_3 volatilization, N_2O emissions, and N leaching) from croplands: options and mitigation strength in a global perspective. Glob Chang Biol 25(6):2077–2093. https://doi.org/10.1111/gcb.14613
9. Pardo G, Moral R, Aguilera E, Del Prado A (2015) Gaseous emissions from management of solid waste: a systematic review. Glob Chang Biol 21(3):1313–1327. https://doi.org/10.1111/gcb.12806
10. Zhou Y, Selvam A, Wong JW (2014) Evaluation of humic substances during co-composting of food waste, sawdust and Chinese medicinal herbal residues. Bioresour Technol 168:229–234. https://doi.org/10.1016/j.biortech.2014.05.070
11. Wang X, Wang W, Zhou B, Xu M, Wu Z, Liang J et al (2020) Improving solid-liquid separation performance of anaerobic digestate from food waste by thermally activated persulfate oxidation. J Hazard Mater 398:122989. https://doi.org/10.1016/j.jhazmat.2020.122989
12. Qasim W, Xia L, Lin S, Wan L, Zhao Y, Butterbach-Bahl K (2021) Global greenhouse vegetable production systems are hotspots of soil N2O emissions and nitrogen leaching: a meta-analysis. Environ Pollut 272:116372. https://doi.org/10.1016/j.envpol.2020.116372
13. Wang B, Zhang P, Guo X, Bao X, Tian J, Li G, Zhang J (2024) Contribution of zeolite to nitrogen retention in chicken manure and straw compost: reduction of NH_3 and N_2O emissions and increase of nitrate. Bioresour Technol 391(Pt A):129981
14. Pan J, Cai H, Zhang Z, Liu H, Li R, Mao H et al (2018) Comparative evaluation of the use of acidic additives on sewage sludge

composting quality improvement, nitrogen conservation, and greenhouse gas reduction. Bioresour Technol 270:467–475
15. Xiong J, Ma S, He X, Han L, Huang G (2021) Nitrogen transformation and dynamic changes in related functional genes during functional-membrane covered aerobic composting. Bioresour Technol 332:125087. https://doi.org/10.1016/j.biortech.2021.125087
16. Kumar Awasthi M, Wang M, Pandey A, Chen H, Kumar Awasthi S, Wang Q et al (2017) Heterogeneity of zeolite combined with biochar properties as a function of sewage sludge composting and production of nutrient-rich compost. Waste Manag 68:760–773. https://doi.org/10.1016/j.wasman.2017.06.008
17. Zhang J, Chen M, Sui Q, Tong J, Jiang C, Lu X et al (2016) Impacts of addition of natural zeolite or a nitrification inhibitor on antibiotic resistance genes during sludge composting. Water Res 91:339–349. https://doi.org/10.1016/j.watres.2016.01.010
18. Waqas M, Nizami AS, Aburiazaiza AS, Barakat MA, Asam ZZ, Khattak B et al (2019) Untapped potential of zeolites in optimization of food waste composting. J Environ Manage 241:99–112
19. Xu Z, Li R, Liu T, Wu S, Xu K, Zhang Y et al (2022) Effect of inoculation with newly isolated thermotolerant ammonia-oxidizing bacteria on nitrogen conversion and microbial community during cattle manure composting. J Environ Manage 317:115474
20. Fu J, Chen S, Tan Y, Zou K, Yu X, Ji L et al (2024) Inoculation of thermophilic bacteria from giant panda feces into cattle manure reduces gas emissions and decreases resistance gene prevalence in short-term composting. J Environ Manage 373:123601. https://doi.org/10.1016/j.jenvman.2024.123601
21. El-Maghraby FM, Shaker EM, Elbagory M, Omara AE, Khalifa TH (2024) The synergistic impact of arbuscular mycorrhizal fungi and compost tea to enhance bacterial community and improve crop productivity under saline-sodic condition. Plants (Basel) 13(5):629. https://doi.org/10.3390/plants13050629
22. Lallemand Animal Nutrition (2023) Slurry inoculants help reduce ammonia emissions, cut fertilizer and labor costs. https://www.lallemandanimalnutrition.com/en/europe/resources/slurry-inoculants-help-reduce-ammonia-emissions-cut-fertilizer-and-labor-costs/
23. Ding J, Wang N, Liu P, Liu B, Zhu Y, Mao J et al (2023) Bacterial wilt suppressive composts: significance of rhizosphere microbiome. Waste Manag 169:179–185. https://doi.org/10.1016/j.wasman.2023.07.011
24. Zhao Y, Li W, Chen L, Meng L, Zhang S (2023) Impacts of adding thermotolerant nitrifying bacteria on nitrogenous gas emissions and bacterial community structure during sewage sludge composting. Bioresour Technol 368:128–359
25. Mao H, Lv Z, Sun H, Li R, Zhai B, Wang Z et al (2018) Improvement of biochar and bacterial powder addition on gaseous emission and bacterial community in pig manure compost. Bioresour Technol 258:195–202
26. Wang S, Niu Q, Zhu P, Huang Y, Li K, Li Q (2022) Metagenomics analysis unraveled the influence of sulfate radical-mediated compost nitrogen transformation process. J Environ Manage 317:115436. https://doi.org/10.1016/j.jenvman.2022.115436
27. Meena MD, Yadav RK, Narjary B, Yadav G, Jat HS, Sheoran P et al (2019) Municipal solid waste (MSW): strategies to improve salt affected soil sustainability: a review. Waste Manag 84:38–53. https://doi.org/10.1016/j.wasman.2018.11.020
28. Shan G, Li W, Gao Y, Tan W, Xi B (2021) Additives for reducing nitrogen loss during composting: a review. J Clean Prod 307:127308
29. Li Y, Song J, Liu T, Lv J, Jiang J (2021) Influence of reusable polypropylene packing on ammonia and greenhouse gas emissions during sewage sludge composting-a lab-scale investigation. Environ Sci Pollut Res Int 28(30):40653–40664. https://doi.org/10.1007/s11356-020-10469-w
30. Mishra A (2023) Suthar S (2015) Bioconversion of fruit waste and sewage sludge mixtures by black soldier fly (Diptera: Stratiomyidae) larvae. Environ Res 218:115019
31. Li S, Li J, Yang S, Zhang Q, Li X, Zhang L, Peng Y (2021) Rapid achieving partial nitrification in domestic wastewater: controlling aeration time to selectively enrich ammonium oxidizing bacteria (AOB) after simultaneously eliminating AOB and nitrite oxidizing bacteria (NOB). Bioresour Technol 328:124810. https://doi.org/10.1016/j.biortech.2021.124810
32. Cáceres R, Malińska K, Marfà O (2018) Nitrification within composting: a review. Waste Manag 72:119–137
33. Zhao Y, Li W, Chen L, Meng L, Zheng Z (2020) Effect of enriched thermotolerant nitrifying bacteria inoculation on reducing nitrogen loss during sewage sludge composting. Bioresour Technol 311:123461
34. Sánchez ÓJ, Ospina DA, Montoya S (2017) Compost supplementation with nutrients and microorganisms in composting process. Waste Manag 69:136–153
35. Yu J, Gu J, Wang X, Guo H, Wang J, Lei L, Dai X, Zhao W (2020) Effects of inoculation with lignocellulose-degrading microorganisms on nitrogen conversion and denitrifying bacterial community during aerobic composting. Bioresour Technol 313:123664. https://doi.org/10.1016/j.biortech.2020.123664
36. Zhu L, Huang C, Li W, Wu W, Tang Z, Tian Y et al (2023) Ammonia assimilation is key for the preservation of nitrogen during industrial-scale composting of chicken manure. Waste Manag 170:50–61
37. Liu X, Wu L, Si Y, Zhai Y, Niu M, Han M et al (2024) Regulating effect of exogenous α-ketoglutarate on ammonium assimilation in poplar. Molecules 29(7):1425
38. van Kessel MA, Speth DR, Albertsen M, Nielsen PH, Op den Camp HJ, Kartal B et al (2015) Complete nitrification by a single microorganism. Nature 528(7583):555–559
39. Daims H, Lebedeva EV, Pjevac P, Han P, Herbold C, Albertsen M et al (2015) Complete nitrification by Nitrospira bacteria. Nature 528(7583):504–509
40. Meng L, Li W, Zhang S, Wu C, Wang K (2016) Effects of sucrose amendment on ammonia assimilationduring sewage sludge composting. Bioresour Technol 210:160–166
41. He X, Xi B, Zhang Z, Gao R, Tan W, Cui D et al (2015) Composition, removal, redox, and metal complexation properties of dissolved organic nitrogen in composting leachates. J Hazard Mater 283:227–233
42. Kuroda K, Waki M, Yasuda T, Fukumoto Y, Tanaka A, Nakasaki K (2015) Utilization of Bacillus sp. strain TAT105 as a biological additive to reduce ammoniaemissions during composting of swine feces. Biosci Biotechnol Biochem 79(10):1702–11
43. Zhang Y, Zhao Y, Chen Y, Lu Q, Li M, Wang X et al (2016) A regulating method for reducing nitrogen loss based on enriched ammonia-oxidizing bacteria during composting. Bioresour Technol 221:276–283
44. Zhang H, Ma L, Li Y, Yan S, Tong Z, Qiu Y et al (2024) Control of nitrogen and odor emissions during chicken manure composting with a carbon-based microbial inoculant and a biotrickling filter. J Environ Manage 357:120636
45. Liu Z, Awasthi MK, Zhao J, Liu G, Syed A, Al-Shwaiman HA et al (2023) Unraveling impacts of inoculating novel microbial This paper will begin with an overview on nitrogen conversion during cattle manure composting: Core microorganisms and functional genes. Bioresour Technol 390:129887
46. Guo H, Gu J, Wang X, Nasir M, Yu J, Lei L et al (2020) Beneficial effects of bacterial agent/bentonite on nitrogen transformation and microbial community dynamics during aerobic composting of pig manure. Bioresour Technol 298:122384
47. Lu Y, Gu W, Xu P, Xie K, Li X, Sun L et al (2018) Effects of sulphur and *Thiobacillus* thioparus 1904 on nitrogen cycle

genes during chicken manure aerobic composting. Waste Manag 80:10–16
48. Park S-J (2009) Microorganisms having bad smell removal activity of organic waste and use thereof. United States Patent Application Publication, US 2009/0208470A1
49. Wilson et al (2021) A bacterial composition capable of degrading complex carbohydrates. World Intellectual Property Organization, WO 2020/030763A1
50. Menicon Co., Ltd., Toyota Jidosha Kabushiki Kaisha (2009) Method of treating biomass, compost, mulching material for livestock and agent for treating biomass. European Patent Application EP 2011 579 A1
51. Chen H, Awasthi SK, Liu T, Duan Y, Ren X, Zhang Z et al (2020) Effects of microbial culture and chicken manure biochar on compost maturity and greenhouse gas emissions during chicken manure composting. J Hazard Mater 389:121908
52. Zhu L, Wang S, Zhang J (2017) A kind of cattle manure composting pro-rotting and nitrogen-preserving bacterial agent and application method. Jiangsu: CN201710084466.8,2017–05–31
53. Wang S, Xu Z, Xu X, Gao F, Zhang K, Zhang X et al (2024) Effects of two strains of thermophilic nitrogen-fixing bacteria on nitrogen loss mitigation in cow dung compost. Bioresour Technol 400:130681
54. Liu N, Liu Z, Wang K, Zhao J, Fang J, Liu G et al (2024) Comparison analysis of microbial agent and different compost material on microbial community and nitrogen transformation genes dynamic changes during pig manure compost. Bioresour Technol 395:130–359
55. Xu Z, Qi C, Zhang L, Ma Y, Li J, Li G, Luo W (2021) Bacterial dynamics and functions for gaseous emissions and humification in response to aeration intensities during kitchen waste composting. Bioresour Technol 337:125369. https://doi.org/10.1016/j.biortech.2021.125369
56. Lu B, Wu X (2018) Effects of composite microbial agent on high temperature composting process and harmful gas emission. J Process Eng 18(1):122–128
57. Xu Z, Li R, Zhang X, Liu J, Xu X, Wang S et al (2023) Mechanisms and effects of novel ammonifying microorganisms on nitrogen ammonification in cow manure waste composting. Waste Manag 169:167–178
58. Bao J, Lv Y, Qv M, Li Z, Li T, Li S et al (2022) Evaluation of key microbial community succession and enzyme activities of nitrogen transformation in pig manure composting process through multi angle analysis. Bioresour Technol 362:127797. https://doi.org/10.1016/j.biortech.2022.127797
59. Gu W, Sun W, Lu Y, Li X, Xu P, Xie K et al (2018) Effect of *Thiobacillus* thioparus 1904 and sulphur addition on odour emission during aerobic composting. Bioresour Technol 249:254–260
60. Wang W, Zhu F, Yao Y et al (2016) A method for preparing a biobacterial agent using a membrane Saccharomyces cerevisiae strain and its application [Patent No. CN201610370836.X]. Zhejiang, China: December 21, 2016
61. Yin H, Liu B, Liu H et al (2018) A bacterium, bacterial agent, and its preparation and application method for deodorizing and preserving nitrogen in poultry manure composting [Patent No. CN201710997226.7]. Hunan, China: January 16, 2018
62. Li D, Chen Y (2020) A bacterial agent for promoting composting and preserving nitrogen in poultry manure and its preparation and application method [Patent No. CN202010694003.5]. Sichuan, China: September 18, 2020
63. Zhang X, Shen Y, Meng H et al (2020) A detonator for aerobic fermentation of cow manure and its preparation method [Patent No. CN202010632575.0]. Beijing, China: October 9, 2020
64. Liu S, Zhang Y, Han L et al (2022) A biological conditioning agent for improving nitrate nitrogen assimilation ability in farmland soil and its preparation method [Patent No. CN202211160904.1]. Jiangxi, China: December 27, 2022
65. Zhong X, Feng S, Dong B et al (2024) A multi-layer thermophilic composite bacterial agent and its preparation method and application [Patent No. CN202311240775.1]. Shanghai, China: January 23, 2024
66. Xu J, Xu X, Liu H et al (2019) A high-temperature micro-aerobic composting nitrogen-preserving bacterium for reducing ammonia volatilization from livestock manure composting and its application [Patent No. CN201811074245.3]. Heilongjiang, China: January 11, 2019
67. Song D, Zhang M, Xiao R (2023) A microbial agent for reducing odor volatilization during manure fermentation and its preparation and fermentation method [Patent No. CN202211723131.3]. Chongqing, China: April 25, 2023
68. WINDFALL BIO INC (2024) Bacterial compositions for methane consumption and nitrogen fixation. World Intellectual Property Organization, WO 2024/197074 A2
69. Gadanakis Y, Bennett R, Park J, Areal FJ (2015) Evaluating the sustainable intensiffcation of arable farms. J Environ Manage 150:288–298
70. Liu J, Nauta J, van Eekert MHA, Chen WS, Buisman CJN (2023) Integrated life cycle assessment of biotreatment and agricultural use of domestic organic residues: environmental benefits, trade-offs, and impacts on soil application. Sci Total Environ 897:165372. https://doi.org/10.1016/j.scitotenv.2023.165372
71. Gaidajis G, Kakanis I (2020) Life cycle assessment of nitrate and compound fertilizers production-a case study. Sustainability 13. https://doi.org/10.3390/su13010148.
72. Skowrońska M, Filipek T (2014) Life cycle assessment of fertilizers: a review. Int Agrophys 28:101–110. https://doi.org/10.2478/intag-2013-0032
73. Ahlgren S et al (2010) Nitrogen fertiliser production based on biogas - energy input, environmental impact and land use. Bioresour Technol 101:7192–7195. https://doi.org/10.1016/j.biortech.2010.04.006
74. Eden M et al (2017) Organic waste recycling in agriculture and related effects on soil water retention and plant available water: a review. Agron Sustain Dev 37:1–21
75. Adhikari K, Hartemink AE (2016) Linking soils to ecosystem services -a global review. Geoderma 262:101–111. https://doi.org/10.1016/j.geoderma.2015.08.009
76. Liu Z, Wang X, Li S, Bai Z, Ma L (2022) Advanced composting technologies promotes environmental benefits and eco-efficiency: a life cycle assessment. Bioresour Technol 346:126576. https://doi.org/10.1016/j.biortech.2021.126576
77. Phong NT (2012) Greenhouse gas emissions from composting and anaerobic digestion plants. Rheinischen Friedrich-Wilhelms University of Bonn
78. Xu Z, Li R, KuoK Ho Tang D, Zhang X, Zhang X, Liu H et al (2024) Enhancing nitrogen transformation and humification in cow manure composting through psychrophilic and thermophilic nitrifying bacterial consortium inoculation. Bioresour Technol 413:131507. https://doi.org/10.1016/j.biortech.2024.131507
79. Zhang Z, Yang H, Wang B, Chen C, Zou X, Cheng T et al (2023) Aerobic co-composting of mature compost with cattle manure: organic matter conversion and microbial community characterization. Bioresour Technol 382:129187. https://doi.org/10.1016/j.biortech.2023.129187
80. Chen Z, Wang Y, Wen Q (2018) Effects of chlortetracycline on the fate of multi-antibiotic resistance genes and the microbial community during swine manure composting. Environ Pollut 237:977–987
81. Ahmed Mohamed T, Wei Z, Mohaseb M, Junqiu W, El Maghraby T, Chen X et al (2024) Performance of microbial inoculation and

tricalcium phosphate on nitrogen retention and conversion: core microorganisms and enzyme activity during kitchen waste composting. J Environ Manage 356:120601

82. Zainul Kamal S, Koyama M, Syukri F, Toda T, Tran QNM, Nakasaki K (2022) Effect of enzymatic pre-treatment on thermophilic composting of shrimp pond sludge to improve ammonia recovery. Environ Res 204(Pt C):112299. https://doi.org/10.1016/j.envres.2021.112299
83. Qiu Z, Li M, Song L, Wang C, Yang S, Yan Z et al (2020) Study on nitrogen-retaining microbial agent to reduce nitrogen loss during chicken manure composting and nitrogen transformation mechanism. J Clean Prod (prepublish):124813
84. He Y, Zhang Y, Huang X, Xu J, Zhang H, Dai X et al (2022) Effect of enriched thermotolerant mechanism of microbial community for carbon conversion and nitrogen fixation during food waste composting with multifunctional microbial inoculation. Bioresour Technol 360:127623
85. Zeng G, Zhang L, Dong H, Chen Y, Zhang J, Zhu Y et al (2018) Pathway and mechanism of nitrogen transformation during composting: functional enzymes and genes under different concentrations of PVP-AgNPs. Bioresour Technol 253:112–120
86. Sun Q, Wu D, Zhang Z, Zhao Y, Xie X, Wu J et al (2017) Effect of cold-adapted microbial agent inoculation on enzyme activities during composting start-up at low temperature. Bioresour Technol 244(Pt 1):635–640
87. Gou C, Wang Y, Zhang X, Lou Y, Gao Y (2017) Inoculation with a psychrotrophic-thermophilic complex microbial agent accelerates onset and promotes maturity of dairy manure-rice straw composting under cold climate conditions. Bioresour Technol 243:339–346
88. Chen Z, Wu Y, Wen Q, Bao H, Fu Q (2020) Insight into the effects of sulfamethoxazole and norfloxacin on nitrogen transformation functional genes during swine manure composting. Bioresour Technol 297:122463
89. Li Q, Guo X, Lu Y, Shan G, Huang J (2016) Impacts of adding FGDG on the abundance of nitrification and denitrification functional genes during dairy manure and sugarcane pressmud co-composting. Waste Manag 56:63–70. https://doi.org/10.1016/j.wasman.2016.07.007
90. Alfonzo A, Laudicina VA, Muscarella SM, Badalucco L, Moschetti G, Spanò GM et al (2022) Cellulolytic bacteria joined with deproteinized whey decrease carbon to nitrogen ratio and improve stability of compost from wine production chain by-products. J Environ Manage 304:114194
91. Ge J, Huang G, Li J, Sun X, Han L (2018) Multivariate and multiscale approaches for interpreting the mechanisms of nitrous oxide emission during pig manure-wheat straw aerobic composting. Environ Sci Technol 52(15):8408–8418. https://doi.org/10.1021/acs.est.8b02958
92. Wen X, Sun R, Cao Z, Huang Y, Li J, Zhou Y et al (2022) Synergistic metabolism of carbon and nitrogen: cyanate drives nitrogen cycle to conserve nitrogen in composting system. Bioresour Technol 361:127708. https://doi.org/10.1016/j.biortech.2022.127708
93. Zhou L, Xie Y, Wang X, Wang Z, Sa R, Li P et al (2024) Effect of microbial inoculation on nitrogen transformation, nitrogen functional genes, and bacterial community during cotton straw composting. Bioresour Technol 403:130859
94. Guo H, Gu J, Wang X, Yu J, Nasir M, Zhang K et al (2020) Microbial driven reduction of N_2O and NH_3 emissions during composting: effects of bamboo charcoal and bamboo vinegar. J Hazard Mater 390:121292
95. Wang Y, Bi L, Liao Y, Lu D, Zhang H, Liao X et al (2019) Influence and characteristics of *Bacillus* stearothermophilus in ammonia reduction during layer manure composting. Ecotoxicol Environ Saf 180:80–87