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专论与综述

超高温堆肥促进氮素减损的微生物机制研究进展

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摘　要：堆肥中氮的循环在很大程度上依赖微生物驱动的氮素转化。传统高温堆肥最高堆温普遍在 55−60 °C，温度的提高有利于缩短堆肥周期和提高堆肥品质。超高温堆肥作为近年来快速发展的新兴技术，不但能突破传统堆肥工艺堆温低的局限，并且持续的超高温调控了堆肥微生物组、堆肥环境与氮素的互作，减少了氮素的损失。本文综述了堆体的氮循环过程及超高温堆肥技术在保氮方面的显著优势，以及超高温堆肥过程中具有氮代谢功能的优势微生物种群及其影响因素，重点介绍有关超高温堆肥控制氮素损失的作用机制研究进展，同时对超高温堆肥现有研究中存在的问题进行分析并探讨解决途径。

关键词：氮素转化；超高温堆肥；优势微生物群落；影响因素

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Progress in the microbial mechanism for the promotion of nitrogen loss reduction by hyperthermophilic composting

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Abstract: Nitrogen cycle within composting is largely dependent on microorganism-driven nitrogen transformation. However, the maximum temperatures of conventional thermophilic composting systems only reach 55–60 °C. Notably, rising the temperature can shorten the duration of processing and improve the quality of end products. Hyperthermophilic composting as an innovative technology has been developed in recent years, breaking through the limitations of low pile temperatures. The continuous ultra-high temperature regulates the interactions between composting microbiome, composting environment, and nitrogen, and thus significantly reduces nitrogen loss. This paper introduced the basic process of nitrogen transformation and the superiority in nitrogen retention during hyperthermophilic composting. Further, we summarized the recent research progress in dominant microbial groups associated with nitrogen transformation, the factors influencing functional microbes, and the mechanism for controlling nitrogen loss in hyperthermophilic composting. Finally, we analyzed the problems in the current research about hyperthermophilic composting and discussed the possible solutions.

Keywords: nitrogen transformation; hyperthermophilic composting; dominant microbial groups; influencing factors

伴随着城乡一体化建设和工农业的发展，大量有机固废产生，这些有机废弃物主要包括市政污泥[1]、农业废弃物[2]、工业固废[3-5]、厨余和餐厨垃圾[6-7]、园林废弃物[8]和畜禽粪便[9-10]等。有效处理有机废弃物已成为许多国家面临的问题。好氧堆肥是有机废弃物的重要处理方式[11]，但传统好氧堆肥存在很多缺陷，例如发酵温度低、堆肥周期长及产品质量不佳[12-17]。近年来，为了克服传统堆肥的弊端并提高推广应用的成效，日本学者将传统堆肥进行改良，提出超高温堆肥这一方法[18]。新型的超高温堆肥技术得以快速发展并引起国内外研究学者的广泛关注[19-21]。

温度是堆肥过程中最显著的参数之一，影响微生物的生长和有机物的降解[13,20]。超高温堆肥技术最显著的特点是发酵温度高(≥80 °C)，最高温度可达 93.4 °C[20]。在适宜的水分条件(60%−65%)和碳氮比(6.6−8.3)的情况下[14,20,22]，该技术并不依赖外源热量，利用超嗜热微生物有氧呼吸代谢释放的生物热使堆体迅速升温，加速有机物的降解并缩短发酵周期，从而快速达到有机固体废弃物的减量化、无害化、资源化及高值化[23]。图 1 展示了关于超高温堆肥的工艺流程[13]，一般在堆肥前期采用添加商业化

的超嗜热菌剂和腐熟物料等接种方式，促使堆体从升温阶段到达超高温阶段[20-22,24-27]并持续5−7 d，随后进入嗜热阶段(50−80 °C)和腐熟阶段(≤50 °C)。

氮素作为重要的营养元素，直接影响堆肥效率和微生物的新陈代谢[28-29]。氮素损失是堆肥过程中不可避免的现象，传统堆肥过程中氮损失量通常为16%−76%，这对生态环境的安全造成了严重隐患[30]。调控堆肥过程中的氮生物转化过程、降低氮损失，对固持产品养分、保护环境和提高堆肥质量具有深远意义。大量研究表明超高温堆肥有效促进氮的积累且显著减少氮素损失[20,24-25,31]，并且在堆肥期间独特的优势微生物菌群变化与氮的代谢密切相关。本课题组前期的研究也证实，优化的微生物群落结构和较高的堆温有利于减少堆肥前期氨的挥发[9]。目前，超高温堆肥促进底物降解与污染物去除或控制机制的论述已有相关报道[14,17]。然而，近几年超高温堆肥过程中氮素转化及其与微生物相关的驱动机制缺乏系统论述和总结，亟须深入探讨。本文以近年来超高温堆肥技术相关文献为基础，一方面聚焦于系统介绍堆体的氮循环过程及超高温堆肥对氮素减损与积累的促进效应；另一方面阐明超高温堆肥过程中具有氮代谢功能的优势微生物种群及其影响因素，以期揭示不同原料的超高温堆肥对氮素减损的促进效应，同时探讨超高温堆肥的优势微生物菌群、堆肥环境与氮素形态三者互作的潜在机制，为今后超高温堆肥过程中功能微生物的添加控制氮素损失的研究提供新思路。

1 堆肥过程中的氮循环

堆体氮循环(图 2)在很大程度上依赖微生物驱动的氮素转化[32]。超高温堆肥的氮循环过程与传统堆肥一致，但是在特定的氮生物转化过程上，其强弱有别于传统堆肥，特别是气态氮的生物转化过程[13-14]。此外，有机氮(酸解有机氮和非酸解有机氮)与无机氮(铵态氮、硝态氮和亚硝态氮)的转化在不同堆肥阶段存在显著差异[28,31-34]。在超高温堆肥过程中的升温阶段，堆体非水溶性有机氮往往通过水解酶的矿化作用形成铵态氮和水溶性有机氮[35]。在超高温阶段，堆料中所积累的一小部分铵态氮在高温和高 pH 值的影响下可通过氨化反应、不完全硝化作用和挥发作用，使得氮素以氨气和氧化亚氮的形式逸散损失[24,35]，但此过程的强度显著

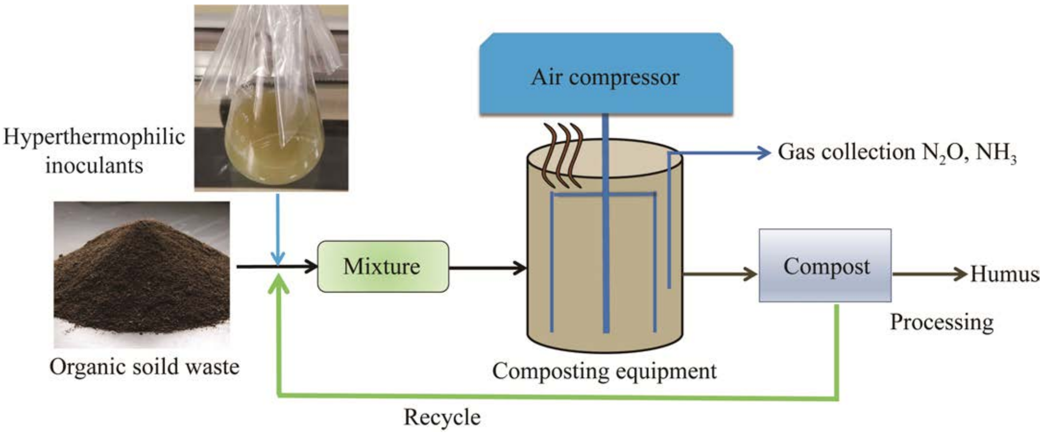

图 1　超高温堆肥的示意图[13]

Figure 1　Schematic diagram of hyperthermophilic composting[13].

低于传统堆肥。此阶段下堆体氮素的转化过程主要是铵态氮在氨氧化细菌/古菌和硝化细菌的介导下形成大量的硝态氮和水溶性氮[20,35]。在超高温过后的嗜热阶段，堆体中大量含氮的前体物质在微生物的作用下，参与梅拉德反应生成以含氮腐殖质为主的非水溶性氮[25]。在降温和腐熟阶段，料堆中的铵态氮和硝态氮分别通过硝化作用以及固氮和固持作用转化为硝态氮和水溶性有机氮[35]。此外，多个氮功能基因在堆肥氮素转化过程中扮演着至关重要的作用[29,36-37]。功能基因氨单加氧酶(*amoA*、*amoB*)、羟胺氧化还原酶(*hao*)和亚硝酸氧化还原酶(*nxrA*)调控硝化过程，硝酸还原酶(*narG*、*napA*)、亚硝酸还原酶(*nirS*、*nirK*)、一氧化氮还原酶(*norB*)和氧化亚氮还原酶(*nosZ*)参与反硝化过程，而钼铁固氮酶(*Nif*)介导固氮作用[29,36-39]。因此，探明堆肥过程中氮功能基因及其寄主微生物的变化是阐明氮素转化机制的关键，这也有助于了解超高温堆肥技术有效控制氮素损失的机制。

2 超高温堆肥对堆肥过程中氮素减损的作用

氨气的挥发是有机废弃物堆肥过程氮素损失的主要途径[6,30]。超高温堆肥可以显著减少氮素损失(表 1)，而且在堆肥过程中抑制含氮废气的排放是促进氮素减损的主要原因[24-25,31]。Huang 等[31]研究发现，在猪粪和秸秆复混的超高温堆肥系统中，堆体的氨化率和铵态氮含量显著降低，这有利于抑制氨气的排放，从而比传统堆肥减少了 49.09%的氮素损失。Cui 等[25]研究发现，通过接种超高温堆肥腐熟回料能够显著降低堆肥过程中氨气的挥发并促进含氮腐殖质的形成，堆肥前后氮素损失比传统堆肥减少近 40.9%。钟广智[35]探究了超高温堆肥对市政污泥堆肥过程中氨气排放的影响，表明在升温阶段超高温堆肥可显著降低氨气的排放速率，而且堆肥前后的氮素损失比传统堆肥减少 86.84%。除了减少氨气的排放，氧化亚氮的控制也是超高温堆肥减少氮素损失的重要途径。Cui 等[24]研究发现，在鸡粪

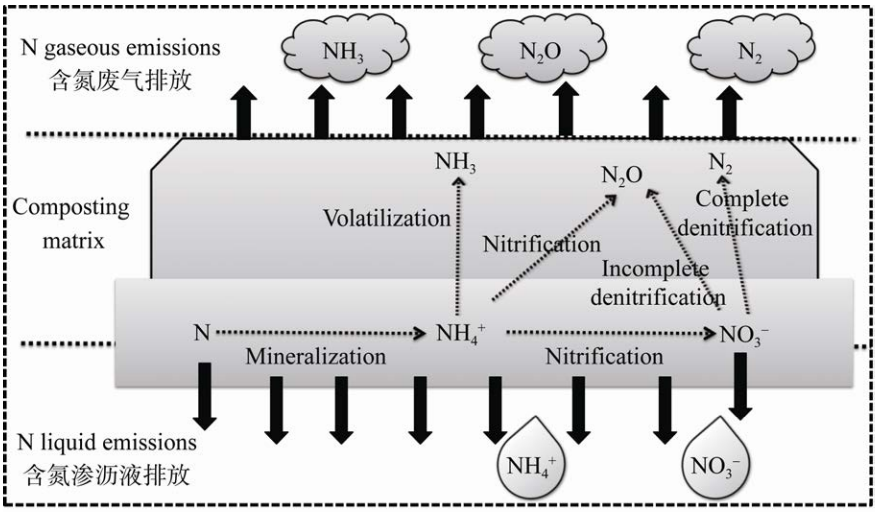

图 2 堆体氮循环[32]

Figure 2 Nitrogen cycle within composting[32].

表 1　超高温堆肥的保氮效应

Table 1　The advantage of nitrogen retention in hyperthermophilic composting

堆肥原料 Composting materials	接种方式 Inoculation method	最高堆温 Maximum temperature (°C)	保氮效应 Nitrogen preserving effect	参考文献 References
猪粪+秸秆 Pig manure+straw	超高温预处理 Hyperthermophilic pretreatment	71.0	比传统堆肥减少 49.09%氮素损失 Hyperthermophilic composting could mitigate nitrogen loss by 49.09% compared to traditional composting	[31]
鸡粪+稻壳 Chicken manure+rice husk	接种 4.3%超高温堆肥腐熟回料 Inoculating 4.3% of end-products from the last hyperthermophilic composting process	88.3	比传统堆肥降低了 52.4%氨气的挥发及减少近 40.9%氮素损失 Hyperthermophilic composting could mitigate NH_3 volatilization by 52.4% and nitrogen loss by 40.9% compared to traditional composting	[25]
脱水污泥+木屑 Dewatered sewage sludge+sawduct	接种 50%超高温堆肥腐熟回料 Inoculating 50% of end-products from the last hyperthermophilic composting process	89.1	比传统堆肥降低了氨气在升温期的排放速率及减少 86.84%氮素损失 Hyperthermophilic composting could decrease NH_3 emission rate in heating stage and mitigate nitrogen loss by 86.84% compared to traditional composting	[35]
鸡粪+稻壳 Chicken manure+rice husk	接种 0.5%超嗜热微生物菌剂 Inoculating 0.5% of hyperthermophilic inoculants	82.6	比传统堆肥降低了硝态氮和亚硝态氮的含量及减少近 90%氧化亚氮排放 Hyperthermophilic composting could decrease NO_3^--N and NO_2^--N concentration and mitigate N_2O emission by 90% compared to traditional composting	[24]
脱水污泥+稻壳 Dewatered sewage sludge+rice husk	接种 22.5%超高温堆肥腐熟回料 Inoculating 22.5% of end-products from the last hyperthermophilic composting process	93.4	比传统堆肥减少 15.48%氮素损失 Hyperthermophilic composting could mitigate nitrogen loss by 15.48% compared to traditional composting	[20]

和稻壳复混的超高温堆肥体系中，氧化亚氮的排放量比传统堆肥减少 90%，而且堆肥前后总氮的损失仅为 0.62%。此外，除了控制含氮废气的排放，超高温堆肥还可通过促进水溶性氮的形成及有机质的降解来提高堆肥产物的全氮含量并减少氮损耗[20]。因此，超高温堆肥技术在保氮方面有着明显优势，有望成为环境友好型的堆肥工艺。

3　超高温堆肥过程中优势的微生物种群及其氮代谢功能

堆肥中氮素形态的转化主要由变形菌门(*Proteobacteria*)和放线菌门(*Actinobacteria*)等微生物驱动[40]。在参与氮素矿化的功能分类上[31]，这些微生物种群包括氨化细菌、硝化细菌、反硝

化细菌和固氮菌等。目前对于传统堆肥过程中氮转化微生物的种类已探明[36,38,41-42]，亚硝化单胞菌属(*Nitrosomonas*)和亚硝化螺菌属(*Nitrosospira*)为典型的硝化细菌，*Pusillimonas*、芽孢杆菌属(*Bacillus*)、施氏假单胞菌(*Pseudomonas stutzeri*)、藤黄单胞菌属(*Luteimonas*)、粪产碱杆菌(*Alcaligenes faecalis*)、脱亚硫酸菌属(*Desulfitobacterium*)、红球菌属(*Rhodococcus*)、卡斯特兰尼氏菌属(*Castellaniella*)及蛭弧菌属(*Bdellovibrio*)为主要的反硝化细菌，而温双歧菌属(*Thermobifida*)、优杆菌属(*Eubacterium*)和毛螺菌科(*Lachnospiraceae*)为固氮菌。现有研究已证明超高温好氧堆肥比传统的高温好氧堆肥具有更高的氮素滞留率，能够有效减少氮素的损失[43]，但对于其控制氮素损失的微生物群落结构需深入探讨。

超高温堆肥不同阶段优势菌群组成差异显著[13]，其氮代谢功能也存在显著差异(表 2)。在升温阶段堆体温度一般为 50 °C 以下[20]，存在大量高氨化活性的假单胞菌科(*Pseudomonadaceae*)等微生物[22]，这些优势菌群通过分泌蛋白酶参与堆肥中蛋白质的生物降解。在经过较短的升温阶段后，堆体温度超过 80 °C 进入超高温阶段，这个过程将显著提高有机质的生物降解率和堆肥产物的腐熟度[20]。一般来说，在超高温

表 2　超高温堆肥过程中优势菌群差异、生态学功能及影响因素

Table 2　Diversity and ecological functions of the dominant microbial groups associated with influencing factors during hyperthermophilic composting

优势菌群 Dominant microbes	堆肥阶段 Composting stage	生态学功能 Ecological functions	影响因素 Influencing factors	参考文献 References
Pseudomonadaceae	升温阶段 Heating stage	氨化活性高并参与蛋白质的降解 Have a stronger ammonifying activities and promote the degradation of proteins	\	[22]
Thermus	超高温阶段 Hyperthermophilic stage	氨化活性低且不参与氨化反应 Low ammonifying activities and is hardly involved in the ammonification	\	[25]
Firmicutes, *Geobacillus*	超高温阶段 Hyperthermophilic stage	反硝化酶活性低 Have a lower denitrification activities	温度(+) Temperature (+)	[35]
Thermoactinomycetaceae	嗜热阶段 Thermophilic stage	分泌脲酶参与有机氮的矿化 Have a high yield in urease and promote the mineralization of organic nitrogen	温度(+) Temperature (+)	[20]
Solibacillus, Unclassified_*Planococcaceae*	嗜热阶段 Thermophilic stage	氨化活性低且参与木质纤维素和甘露醇的降解 Low ammonifying activities and posses a high degradation capacity on lignocelluloses and mannitol	可溶性有机碳(+) Dissolved organic carbon (+)	[31]
Aspergillus	腐熟阶段 Maturation stage	氨化活性低且参与木质素的降解 Low ammonifying activities and can degrade lignin	总氮(+) Total nitrogen (+)	[31]

注：(+)：该优势菌群与环境因素正相关；\：未对该阶段优势菌群的影响因素开展研究

Note: (+): The dominant microbes had positive associations with environmental factors; \: The influencing factors of dominant microbial community in this stage were not studied.

阶段的优势微生物菌群大多分布于栖热菌门(*Thermi*)和厚壁菌门(*Firmicutes*)的栖热菌属(*Thermus*)和芽孢杆菌属(*Bacillus*)、中华芽孢杆菌属(*Sinibacillus*)和地杆菌属(*Geobacillus*)。其中，*Thermus* 具有较低的氨化活性，并不参与堆体氮素的氨化反应[25]；而与氮素转化酶呈显著负相关的 *Bacillus*、*Sinibacillus* 和 *Geobacillus* 则具有较低的反硝化酶活性，能够显著降低高温下的反硝化强度[35]。因此，这些独特的优势微生物菌群在超高温阶段减少氮素损失上具有至关重要的作用。经过超高温阶段，在堆体嗜热阶段的优势菌群大多分布于高温放线菌科(*Thermoactinomycetaceae*)[20]、土壤芽孢杆菌属(*Solibacillus*)和动球菌科(unclassified_*Planococcaceae*)[31]，它们主导着堆体有机物质的水解代谢。其中，*Thermoactinomycetaceae* 可通过分泌脲酶促进堆体有机氮的矿化[20]，而低氨化活性的 *Solibacillus* 和 unclassified_*Planococcaceae* 与基质中木质纤维素和甘露醇的降解密切相关[31]。经过嗜热阶段，堆肥基质中易降解有机物和营养物质不足，嗜热微生物种群代谢活性减弱，堆体温度逐渐下降，进入腐熟阶段[44]。一般来说，超高温堆肥腐熟阶段的优势微生物种群分布于嗜热真菌曲霉菌属(*Aspergillus*)，这种高丰度的锁氮微生物种群不参与堆体的氨化反应，但通常参与木质素的降解[31]，并且能够将堆料内的铵态氮转化为硝态氮和菌体凯氏氮[45]。因此，超高温堆肥减少氮素损失的主要原因是：一方面其促进了超嗜热和嗜热菌群的生长，另一方面这些菌群具有极低的氨化活性。

4 超高温堆肥控制氮素损失的作用机制

堆肥过程中氨化菌群和硝化菌群的数量及其分泌的功能酶主导着氮素的生物转化，并且氮素特定的赋存形式对于提高氮的滞留和减少氨的挥发起到关键的调控作用[32,46]。近年来，分子生态学技术和数理统计模型方法得到迅猛发展，高通量测序技术、结构方程模型(structural equation models，SEMs)和偏最小二乘法路径模型(partial least squares path modeling，PLS-PM)被广泛应用于堆肥研究，不仅极大地拓展了人们对堆肥过程中微生物群落组成与演替规律的认识[47]，而且清晰地阐明了环境因素、核心微生物群落和关键物质组成等多元变量之间的内在关系及互作机制[22,48-50]。当然，这些研究手段也为解析超高温堆肥显著减少氮素损失的酶促机制和微生物学机制提供了便利。

表 3 总结了超高温堆肥促进氨气和氧化亚氮减排的相关机制及其影响因素。对于控制氨气的排放，超高温堆肥主要通过降低堆体蛋白酶活性、脲酶活性和氨化菌群丰度[假单胞菌属(*Pseudomonas*)、芽孢杆菌属(*Bacillus*)、枝顶孢霉菌属(*Acremonium*)、链格孢菌属(*Alternaria*)和青霉菌属(*Penicillum*)]并促进含氮腐殖质等物质的大量生成，从而降低堆肥过程中氨化反应的速率和强度[25,31]。此外，超高温堆肥通过抑制多种氮素转化酶活性和氮功能基因表达控制氮氧化物的排放。在酶促机制上，超高温堆肥显著提高了与反硝化酶有显著负相关的 *Firmicutes* 相对丰度并降低由绿湾菌门(*Chloroflexia*)和酸杆菌门(*Acidobacteria*)产生的硝酸还原酶活性、亚硝酸还原酶活性及其所介导酶促反应中底物的含量[35]；然而在功能基因调控上，超高温堆肥削减了堆肥过程中 *amoA* 基因数量和反硝化基因数量，促进了氧化亚氮的减排[24,35]。此外，堆肥微环境的理化性质(堆肥原料组成、温度、pH 值、C/N 和含水率)、堆肥工艺(堆肥体系的开放程度和规模、翻堆频率和

通风速率等)及微生物群落结构均对堆肥过程中氮素的损失途径和程度产生显著影响[6,30,32,35,51]。超高温堆肥技术能够通过对温度、含水率、微生物生物量碳和碳氮比等堆肥环境及微生物多样性的调控[24-25,35]有效地减少好氧堆肥的氮素损失。然而目前主控超高温堆肥过程中含氮废气排放的影响因素已被阐明(表 3)。研究[25]表明，细菌丰度是氨气减排环节的重要控制参数，超高温堆肥过程中细菌丰度的变化显著抑制了氨气的排放。除了细菌丰度外，温度和微生物生物量显著抑制超高温堆肥过程中氧化亚氮的排放[24]，而 pH 值的升高促进了氮氧化物的排放[35]。

5 超高温堆肥过程中氮素转化的影响因素

不同的环境因子(pH、C/N 和养分)通过影响微生物生长和代谢而直接或间接影响堆肥功能[52]。因此，明确环境因子对超高温堆肥过程中氮素转化的影响，特别是阐明这些因素对不同阶段优势微生物种群生长的影响有利于减少氮素损失。堆体温度和养分状况是超高温堆肥过程中具有氮代谢功能的优势微生物种群结构最重要的影响因素(表 2)。超高温堆肥初期由于堆肥基质中易降解的有机物快速分解而产生极端高温，超高温促进了 *Firmicutes*、*Geobacillus*

表 3 超高温堆肥减少氮素损失的机制

Table 3 The mechanisms of reducing nitrogen loss by hyperthermophilic composting

控制氮素损失的主要途径 Main ways for controlling nitrogen loss	控制氮素损失的机制 Mechanisms for controlling nitrogen loss	含氮废气减排的影响因素 The influencing factors of nitrogenous gas emission reduction	参考文献 References
氨气排放 Ammonia emission	显著降低堆体中蛋白酶活性、脲酶活性、氨化菌群丰度并促进含氮腐殖质等物质的大量生成从而降低氨化速率 Significantly decreased protease and urease enzyme activities and ammonifier relative abundance, meanwhile enhanced the formation of nitrogenous humic substances and reduced the ammonification rate	细菌丰度(−) Bacterial abundance (−)	[25]
	显著降低堆体中蛋白酶活性、脲酶活性和氨化菌群的丰度从而降低氨化反应的速率和强度 Significantly decreased protease and urease enzyme activities and ammonifier relative abundance, meanwhile reduced the ammonification rate and intensity	\	[31]
氮氧化物排放 Oxynitride emission	显著降低硝酸还原酶活性和亚硝酸还原酶活性并在堆肥中后期显著削减反硝化基因数量从而降低反硝化强度 Significantly decreased nitrite reductase and nitrate reductase enzyme activities, and had lower relative abundance of denitrification functional genes in the middle and late stage of composting, meanwhile reduced the denitrification intensity	pH (+)	[35]
氧化亚氮排放 Nitrous oxide emission	显著降低堆肥过程中 *amoA* 基因和 *norB* 基因的相对丰度及硝态氮和亚硝态氮的含量 Significantly decreased the relative abundance of *amoA* and *norB* and reduced the NO_3^--N and NO_2^--N concentration	温度(−)和微生物生物量(−) Temperature (−) and microbial biomass (−)	[24]

注：(+)：该因素促进含氮废气的排放；(−)：表示该因素抑制含氮废气的排放；\：未对含氮废气减排的影响因素开展研究

Note: (+): The factors promoted nitrogenous gas emission; (−): The factors controlled nitrogenous gas emission; \: The influencing factors of nitrogenous gas emission reduction were not studied.

和 *Thermoactinomycetaceae* 的大量繁殖[20,35]。相较于温度，堆体养分的改变也会影响优势微生物菌群的组成。在嗜热阶段，可溶性有机碳的增加为 *Solibacillus* 和 unclassified_*Planococcaceae* 的大量生长提供了充足的能量[31]。然而在腐熟阶段，堆体总氮的升高可促进 *Aspergillus* 的快速生长[31]。由此表明，在超高温堆肥中，具有氮代谢功能的优势微生物群落结构在不同堆肥阶段的影响因素有所差异，可通过堆肥期间调节相应的环境因子来降低氨化菌群的丰度和活性，从而减少氮素的损失。

除了微生物群落，环境因子还对超高温堆肥期间氮功能基因的相对丰度具有显著的调控作用[24]。在超高温堆肥系统中，温度均与 *nirK*、*narG*、*nosZ* 和 *nirS* 等功能基因的相对丰度之间存在显著的正相关关系[24]，表明温度的升高有利于更多的氧化亚氮转化为 N_2。类似地，超高温堆体的 pH 与 *amoA* 和 *norB* 基因的相对丰度之间存在显著的正相关关系[24,35]，表明较高的 pH 值有利于削减 *norB* 基因的相对丰度，而电导率(electrical conductivity，EC)和微生物生物量氮与 *amoA* 和 *norB* 基因的相对丰度之间存在显著的负相关关系[24,35]。此外，超高温堆肥过程中氮素转化酶(硝酸还原酶和亚硝酸还原酶等)对参与反硝化过程的氮功能基因的相对丰度也具有正调控作用[35]。因此，超高温堆肥凭借独特的理化环境显著影响参与氮素转化的功能微生物群落，有效减排含氮的温室气体。

6 问题与展望

现有对超高温堆肥的研究表明，其在技术经济成本、快速降解有机质、减少氮素损失和产品的清洁生产上存在明显的优势[35,53]。因此，相较于传统堆肥，超高温堆肥在环境治理领域的研究有非常广阔的前景。微生物在堆肥氮素转化中发挥了主导作用[54]，加深对超高温堆肥在不同阶段具有氮代谢功能优势微生物种群的动态变化和代谢网络[55]研究，对于解析有机氮组分微生物代谢网络有序性原理、提高堆肥产品的氮素滞留率及减少堆肥过程中恶臭与温室气体排放具有重要意义。超高温堆肥促进氮素减损的微生物机制主要是其显著调控了超高温阶段、高温阶段及腐熟阶段的微生物群落结构，这些优势菌群及其携带的功能基因在氮循环过程的各个步骤发挥了关键作用[56] (图 3)。简而言之，超高温堆肥过程中高丰度的 *Thermus*、*Solibacillus* 和 *Aspergillus* 等优势菌群主要参与碳降解，因而堆体的氨化酶活性和氨化速率显著降低；另一方面，超高温堆肥过程中高丰度的 *Bacillus*、*Sinibacillus* 和 *Geobacillus* 显著削减了反硝化过程功能基因的丰度，使堆体氧化亚氮的释放速率降低。然而，由于试验规模的放大更易受到诸多外界因素的影响，现阶段超高温堆肥在国内外仍处于探究阶段[14]，也面临着许多问题，主要有以下几点：

(1) 目前在微生物代谢网络养分定向转化的调控机制研究上，超高温堆肥的研究已阐明温度和微生物生物量是影响有机物质氮代谢全过程的主控因子[24]，但是主控因子如何调控其他因素来改变氧化亚氮排放速率及其动力学机制[57]是未来的研究热点。

(2) 虽然现有研究探明了超高温堆肥可促进含氮腐殖质的大量形成并减少氨化反应的底物从而减少氮素损失[25]，但腐殖化过程对于控制氮素损失的作用机制尚不明确。

(3) 已有研究表明，接种适宜比例的专用嗜热复合菌剂(嗜热脲芽孢杆菌、土芽孢杆菌、嗜热脱氮芽孢杆菌、红嗜热盐菌和嗜热栖热菌)显著促进了超高温堆肥的腐熟进程[12]，而关于超高温堆肥专用菌剂的种类和接种方式对堆肥过

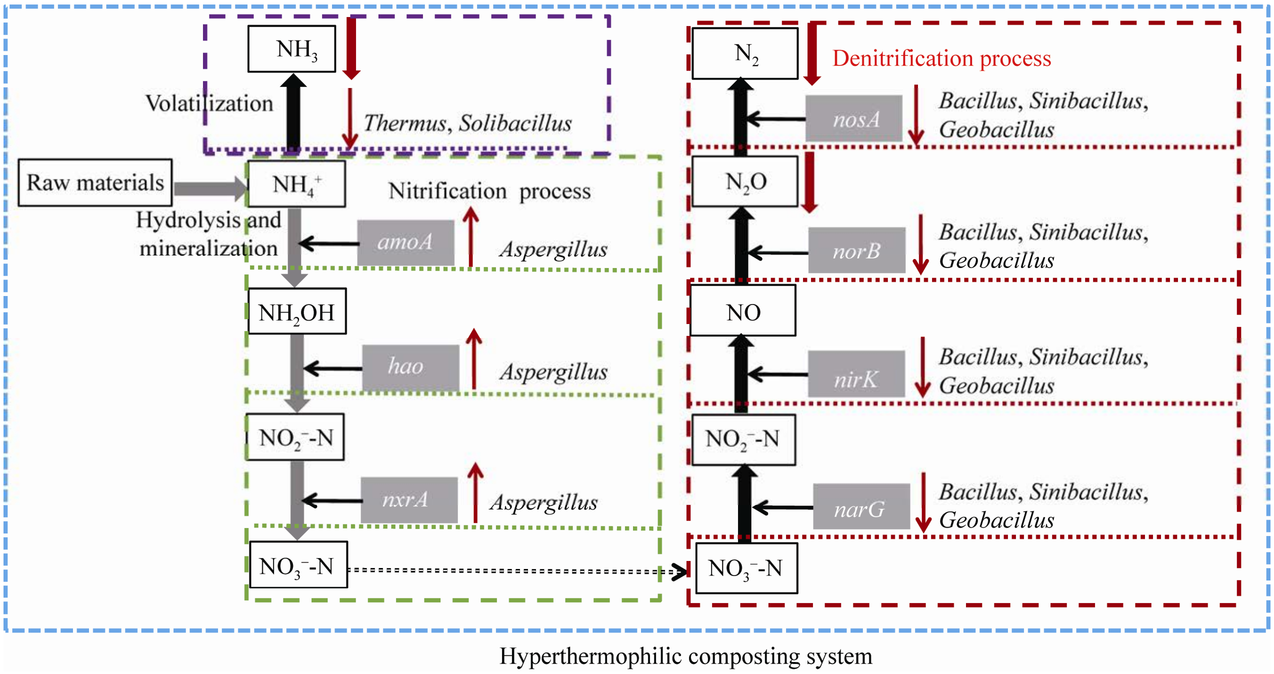

图 3　超高温堆肥对堆肥过程 NH_3 和 N_2O 释放的影响机制

Figure 3　Mechanism concerning the effects of hyperthermophilic composting on NH_3 and N_2O emission in composting process.

程中氮素转化、腐殖质及其土著菌群的影响及影响机制鲜有研究[43,58]。

(4) 堆体中不同的有机氮成分会显著影响铵态氮的含量[28,33-34]，这直接影响含氮废气的排放量，而外源添加这些有机氮成分对超高温堆肥过程中氮素转化的影响及其酶学机制尚不可知，值得进一步研究。

(5) 碳源不足是堆体氮素损失较大的重要原因[59]，而超高温堆肥初始的碳氮比一般较低，但其能够促进含氮腐殖质的形成从而减少氮素损失[25]。此外，由细菌群落所主导的氨基酸代谢与碳水化合物代谢是维系堆体腐殖质形成的中心环节[40]。因此，超高温堆肥如何调控由核心微生物主导的碳氮代谢用于促进含氮腐殖质形成，这其后的耦合机制有待于阐明。

基于存在的问题，超高温堆肥对有机固废资源化利用的研究可以从以下方面继续开展：探索不同来源废弃物的超高温堆肥工艺[13]，即通过数学模型对各个工艺参数进行优化，筛选出最佳工艺组合以减少氮素损失[35]；为消除共存污染物对堆肥氮素转化的不利影响[37]，研制适用性广并高效降解污染物的嗜热硝化菌剂，研究接种功能菌剂促进超高温堆肥过程中污染物降解和减排氧化亚氮的机制[60]；为克服最高堆温滞后的局限[5,9]，将继续筛选具有保氮除臭功能的高温菌剂并通过分阶段接菌的策略[3,61]，以促进易腐垃圾堆肥过程中堆温的起爆和氮素的滞留。

随着研究手段的不断发展及基础研究的不断深入，在不同规模下对超高温堆肥阻控氮硫污染物的探索可以更进一步，同时应当致力于将超高温堆肥产品运用于生产实践中，为农业产地环境的治理开拓一条绿色安全的道路。

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