畜禽养殖场粪便清扫、堆积及处理单元氮损失率研究

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摘　要: 畜禽粪便还田利用是规模养殖场污染治理与控制的有效措施。畜禽粪便从出舍到农田施用,其氮素会有不同程度的损失,对其定量估算有利于畜禽粪便处置或资源化过程中的氮素管理。在总结国内外已有研究报道的基础上,结合本研究室最新的研究成果,探讨了猪粪、牛粪和禽粪在清扫、堆积、高温堆肥、厌氧发酵和沼液贮存这5个单元的氮损失率,估算了畜禽粪便3条主要处理利用途径的氮素实际入田率,分别为:清扫→堆积→还田(29%~80%N,均值为55%N);清扫→堆积→高温好氧堆肥→还田(6%~56%N,均值为31%N);清扫→厌氧发酵→沼液贮存→还田(9%~51%N,均值为30%N)。旨在为农田负荷量估算、种养结合的农作物种植面积配置、养殖场废弃物污染风险分析及其防治技术制定等提供科学依据。

关键词: 畜禽粪便;处理单元;氮损失

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Nitrogen Loss During Cleaning, Storage, Compost and Anaerobic Digestion of Animal Manures in Individual Treatment Unit

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Abstract: Modern livestock production systems, based on intensification in large farms, produce huge amount of manures and slurries, which must be managed under appropriate disposal practices to avoid a negative impact on the environment. Compost is increasingly considered as a good way for manure treatment with economic and environmental profits, since this process eliminates or reduces the risk in terms of pathogen, parasite and weed seed spreading associated with direct land application of manure and leads to a final stabilized product. Recently, animal wastes have been successfully employed in anaerobic biogas production, which was viewed as a pragmatic approach to rationalize energy costs in animal farms. The digested slurries application as fertilizers is increasingly considered as a good way for recycling the surplus of manure for agriculture, and much research work has been carried out in the last decade. However, after manures clean from barns, nitrogen in manures would loss to varying degrees before farm application, Nitrogen losses impact negatively on the manure composting process, by decreasing nutrient concentration, reducing compost quality, and generating health and environmental problems. Nitrogen losses through composting can occur by NH_3 volatilization, leaching and denitrification. In addition, nitrogen in manures could loss during the anaerobic digestion and the storage of digested slurries. The nitrogen content in manures cannot indicate the actual amount of nitrogen entered to farmlands. In order to understand nitrogen loss rate in manures and their actual application rate to farmlands, the first part of this paper reviewed the information on nitrogen loss in units of cleaning, storage, composting, anaerobic digestion of manures in the literature. Then, the latest research results from our group such as nitrogen losses from composting and anaerobic digestion of pig, dairy and poultry manures was presented. On the basis of literature review and our investigation, three treatment routes of manures and their nitrogen inputs to farmlands were proposed, i.e. via cleaning and storage (29%~80%N input with 55%N on average), composting (6%~56%N input with 31%N on average), and anaerobic digestion(9%~51%N input with 30%N on average). Special attention should be paid to the nitrogen loss of manures in each treatment unit for providing scientific basis on the estimation of nitrogen load, allocation of planting area, evaluation of pollution risks and establishment of control criteria.

Keywords: animal manures; treatment unit; nitrogen loss

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随着集约化饲养程度的不断提高，畜禽养殖废弃物已成为影响我国环境质量的重要污染源之一[1]。根据国家环境保护部2010年发布的“全国第一次污染源普查公报”数据，全国畜禽养殖业粪便年产量为2.43亿t[2]。畜禽粪便中的氮素已成为农业面源污染的主要来源[3-5]，规模养殖场粪污治理已成为农业面源污染防治的重中之重。

农牧结合是畜禽养殖污染治理与控制最重要和有效的措施之一，目前国际上普遍的做法是将畜禽粪便作有机肥还田利用[7]。畜禽粪便经过清扫、收集、贮存、处理到农田施用，其中的氮素会有相当数量的损失，直接以畜禽粪便的含氮量为依据势必影响其农田负荷量估算、农作物种植面积配置以及养殖场废弃物污染风险分析及其防治技术制定等问题。本文在总结国内外已有研究报道的基础上，结合本研究室的研究成果，探讨了猪粪、牛粪和禽粪在出舍、堆积、高温堆肥、厌氧发酵和沼液贮存这5个处理单元的氮损失，旨在为畜禽粪便在农田的合理施用以及养殖场废弃物污染控制提供科学依据。

1　粪便清扫和堆积过程中的氮损失

1.1　粪便清扫中的氮损失

清扫出舍是粪便处理或利用的第一步，合理的清粪方式可以在前端有效控制畜禽粪便的污染。目前我国主要的清粪方式有3种：干清粪、水冲粪和水泡粪（自流式），规模养殖场主要采用干清粪方式[8]。不同清粪方式下粪便中氮流失量不同。干清粪可以提高固体粪便的收集系数，与水冲粪工艺相比，氮素损失可降低57.6%[9]；同时，干清粪迁移到水中的全氮只为水冲粪的28.3%，进入水体的全氮负荷量仅为水冲粪的17.4%[10]，显著降低其中氮素向水体的迁移[10]及氨挥发损失[11-12]。但已有的研究对不同清粪方式下粪便氮损失的报道较少，仅有对猪场粪便每天刮除和清运过程中氮损失的调查，其结果发现粪便的氮损失率为20%~35%[12]。因此，量化畜禽粪便清扫过程中氮素的损失在今后的研究中有待进一步加强。

1.2　粪便临时堆积中的氮损失

清理出舍的粪便临时堆积是其氮损失的一个主要途径。特别是在规模化养殖场，由于粪便产生量大，大部分未经处理直接露天存放，有些甚至存放相当一段时间后才运至田间[13]。在此过程中，氮素通过氨挥发损失率高达29%[14]，通过径流损失0.8%~4%[15-16]；约22%的氮素进入水体[17]，加剧了周围水域水体氮富营养化[2]。汇总已有报道发现，在堆积过程中猪粪、牛粪和禽粪的氮损失率分别为10.0%~40.0%[10,15,18]、0.1%~49.1%[19-21]和30.0%~60.0%[22-24]，均值分别为26.3%±2.1%、23.8%±6.7%和45.0%±15.0%。

为定量估算畜禽粪便在不同堆积条件下的氮损失量，本研究室对猪粪、奶牛粪及鸡粪在常温（20℃）及低温（<10℃）条件下进行了3个堆放高度的试验（表1）。研究发现：常温（20℃）下堆积的粪便其氮损失率高于低温（<10℃）；猪粪堆积40 d后氮损失率为18.1%~27.2%，奶牛粪（加稻壳）堆积30 d后氮损失率为0.2%~8.4%，鸡粪堆积30 d后氮损失率为19.0%~20.7%，这与已有的报道结果一致[10,14-16,18-24]。猪粪和奶牛粪中氮损失率随着其堆放高度的增加有降低的趋势。

表1　猪粪、奶牛粪和鸡粪堆积后的全氮含量及其损失率

Table 1　Content of nitrogen and its loss rate after storage of pig, dairy and poultry manures

粪便类型	堆积时间/d	堆体高度/cm	全氮含量/g·kg^{-1}		氮损失率/%	
			常温（>20℃）	低温（<10℃）	常温（>20℃）	低温（<10℃）
猪粪	40	30	16.69	—	27.2	—
	40	40	19.37	—	23.6	—
	40	50	21.49	—	18.1	—
奶牛粪	30	30	18.97	19.67	8.4	5.2
	30	40	19.34	20.17	2.6	2.6
	30	50	18.77	20.79	0.2	1.2
奶牛粪+稻壳（质量比50:1）	30	30	19.27	18.61	1.9	1.2
	30	40	19.17	19.12	2.9	3.7
	30	50	18.64	19.08	2.5	9.8
鸡粪	30	30	18.91	24.98	19.0	16.5
	30	50	18.89	24.19	18.2	12.5
	30	70	17.61	23.36	20.7	14.1

2 粪便高温好氧堆肥过程中的氮损失

高温好氧堆肥是固体粪便最佳的处理方式之一[7]。此过程中由氨化、硝化、反硝化、气体释放(如 NH_3、N_2、N_2O)和生物吸收固定等作用造成的氮损失很大,最高可达 78%[25]。国内外对畜禽粪便高温堆肥过程中氮素变化有大量的报道,本文仅选择 1990——2012 年间,试验条件清晰且有明确氮损失结果的文献进行了汇总分析,发现:纯粪便堆肥过程中,猪粪、牛粪和禽粪的氮损失率范围分别为 13.4%~39.8%[25-31]、8.8%~46.3%[20,32-36]和 15.0%~58.0%[37-41],均值分别为 33.2%±7.2%、26.8%±7.9%和 34.5%±12.6%(图 1a);添加碳含量较高的辅料后堆肥,猪粪、牛粪和禽粪的氮损失率范围分别为3.0%~60.0%[30,42-57]、5.0%~50.0%[44,55,58-63]、7.7%~76.0%[38,44,64-69],均值分别为 34.0%±2.7%、26.1%±3.9%和 36.3%±5.2%(图 1b),对减少氮损失的作用有限。

3 粪便厌氧发酵及沼液贮存过程中的氮损失

3.1 粪便厌氧发酵中的氮损失

厌氧发酵产沼气技术是规模化畜禽养殖场粪便污染治理的有效途径之一[70],特别是对于液体粪便(与固体粪便的分界线大致在水分含量 80%)的管理具有极为重要的作用[71]。以规模化沼气工程为核心的处理模式发展十分迅速,截至 2010 年 7 月底,全国大中型养殖场沼气工程近 5000 处[72-73],年产沼液和沼渣量已超过 1.3×10^9 t[1]。尽管在厌氧发酵过程中粪便中的氮有 1.2%~12.2%的损失[74-77],但更多的氮仍然保留在沼液和沼渣中[77-78],可以作为肥料还田利用[79]。

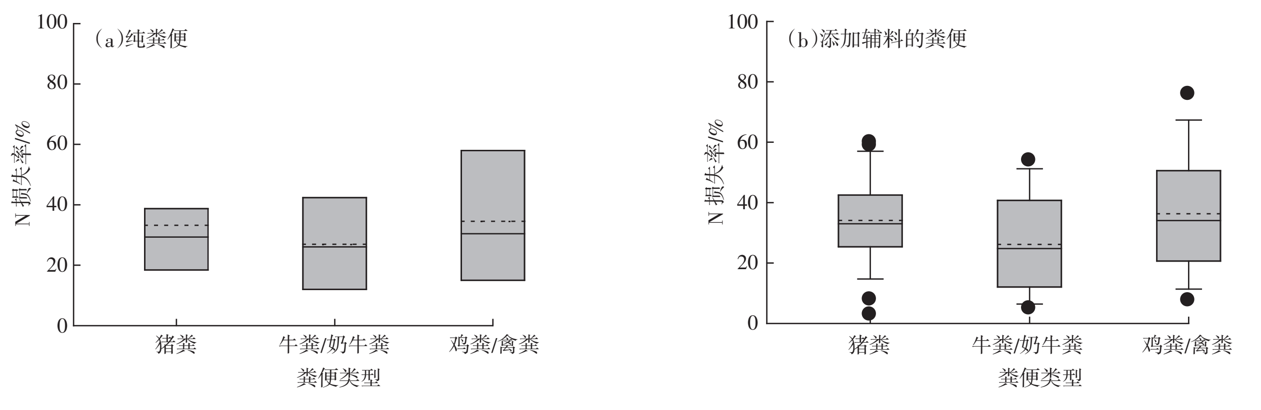
由于厌氧发酵中微生物作用[80-82],残留的氮素在液相和固相中的分配比例及形态(如铵态氮和硝态氮)会发生重要的改变[78-79],直接影响到沼液的田间运筹方式和无害化处理。本研究室在定量分析厌氧发酵过程中氮素总量变化基础上[76],进一步分析了氮素形态转化及在固相和液相的分配。研究结果表明:发酵后的出料中,猪粪的氮量相对进料,在液相中增加了约 10.7%,在固相中降低了约 28.0%;而牛粪的氮量在液相中降低了约 8.7%,在固相中增加了约 2.8%(图2a)。猪粪和牛粪发酵出料中 NH_4^+-N 的质量占总氮量的 43.3%和 30.5%(图 2b),增幅分别达 162.2%和90.0%,这大大增加了沼液还田过程中的 NH_3 挥发风险。

3.2 沼液贮存中的氮损失

排出发酵罐的沼液和沼渣往往不能马上还田,多数情况下需要贮存一段时间。沼渣数量较少,通常直接堆放或做堆肥;而沼液数量大,后处理困难,通常在储液池或氧化塘内贮存。本研究室调查发现[83]:沼液中全氮和铵态氮的总质量随着贮存时间的增加而大幅度减少(图 3);在冬春季(2—5 月)贮存 30、60 d 和 90 d 后, 全氮的总质量分别降低 36.4%、67.2%和 84.8%,而在夏秋季(7—9 月)则分别降低 49.1%、74.9%和 76.3%;加盖可以降低沼液贮存过程中氮损失的风险,但效果有限(仅为 0.6%~4.4%)。

4 畜禽粪便不同处理途径下氮素还田率的估算

集约化养殖场产生的富含氮磷等养分的粪便和污水作为有机肥料还田利用,是最经济、简便的粪污治理方式。国内已经对畜禽粪便产生量[2]、农田负荷量[84]、还田适宜施用量及其匹配农作物种植面积[85]、污染风险分析及其防治技术规范进行了大量的研究与制定



箱体上线、中线和下线分别表示第三四分位、中值和第一四分位值;虚线表示平均值;
最上方和最下方的线段分别表示最大值和最小值;黑点表示异常值

图 1 已有文献中畜禽粪便高温堆肥后的氮损失率

Figure 1 Nitrogen loss rate during composting of manures from other literatures

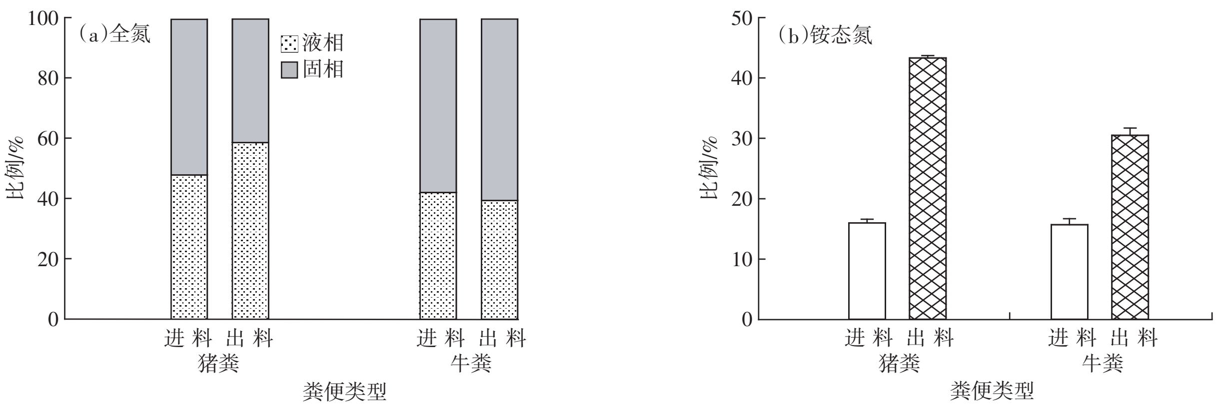


图2 发酵前后氮素在固相和液相中所占的比例

Figure 2 The ratio of nitrogen in solid and liquid fraction of slurry during the anaerobic digestion

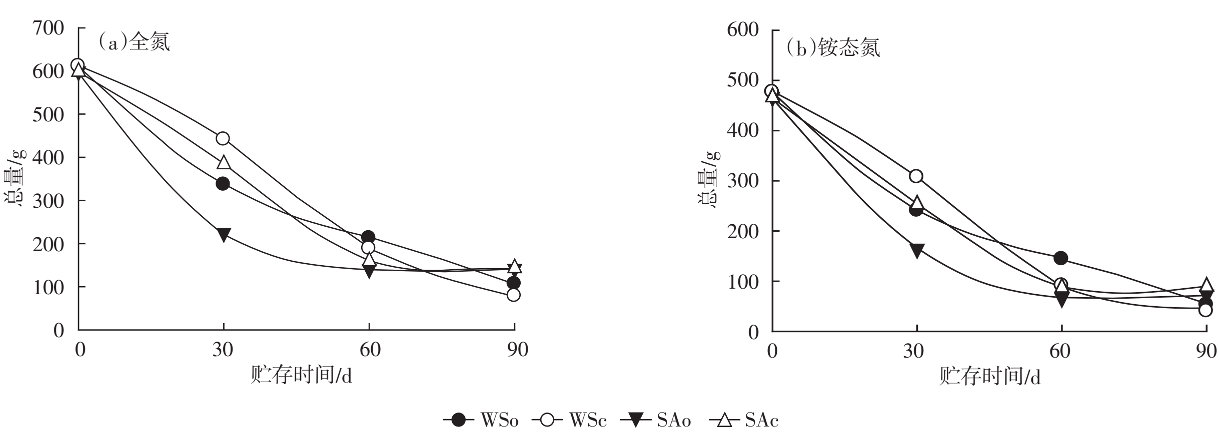
工作[86-88]。从畜禽粪便的收集到农田施用，不同环境条件及处理方式下最终进入农田的氮量不尽相同；以粪便中的氮量为依据，难以精确地对畜禽粪便农田负荷量进行估算以及对农牧结合时农作物种植面积进行科学配置，不利于养殖场废弃物污染风险分析及其防治技术制定等工作。

根据已有报道及本研究室研究结果，笔者总结了猪粪、牛粪和禽粪进入农田的3条主要途径，即经堆积后直接入田（R1）、经高温好氧堆肥后入田（R2）、经厌氧发酵后入田（R3），以及粪便中的氮在各单元的损失率和最终入田量（图4）。从整理结果可以看出：

（1）在清扫单元，畜禽粪便中的氮约有20%~35%（平均值±标准误：27.5%±7.5%）的损失。必须说明的是，定量测定畜禽粪便在清扫过程中的氮损失存在难度，可参考的研究结果较少。本文仅采用了Pohl[12]对猪粪清扫收集的研究结果，因此估算数值可能存在偏差，需要后续更多的相关研究数据进行修正。

（2）在临时堆积单元，畜禽粪便中的氮损失率变幅较大[0.1%~60%，其中：猪粪、奶牛粪及鸡粪氮损失率（平均值±标准误）分别为：26.3%±2.1%、23.8%±6.7%、45.0%±15.0%]，直接影响了后续各环节的氮素利用率。因此，一方面应减少粪便存放的时间，另一方面应合理控制存放条件，减少氮素的损失。

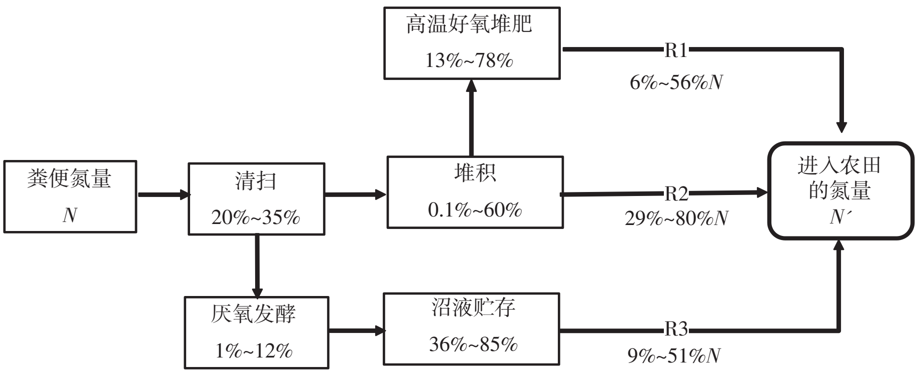
（3）在资源化利用处理单元，厌氧发酵（平均值±标准误为6.4%±1.9%）比高温好氧堆肥[猪粪、奶牛及鸡粪氮损失率（平均值±标准误）分别为：33.9%±2.6%、26.2%±3.4%、36.0%±4.7%]更有利于畜禽粪便中氮素的保留，氮损失降幅约为36%。但在生产实际中，从粪便出舍到进入厌氧发酵前，还需要经过径流、调节池或酸化池等流程，这些流程中也会发生氮素损失，目前，对于粪便出舍后至厌氧发酵前这一过程中氮的损失率未见相关报道，因此，还有待后续的相关研究结



WSo：冬春季无盖；WSc：冬春季有盖；SAo：夏秋季无盖；SAc：夏秋季有盖

图3 沼液在贮存过程中氮素总质量的变化

Figure 3 Change of nitrogen content in anaerobically digested pig slurry during its storage



途径 1(R1):畜禽粪便清扫→堆积→还田

途径 2(R2):畜禽粪便清扫→堆积→高温好氧堆肥→还田

途径 3(R3):畜禽粪便清扫→厌氧发酵→沼液贮存→还田

方框内数值表示粪便中氮的损失率 f_i;最终进入农田的氮量(N')的计算公式:$N'=\frac{N\times(100-f_i)}{100}$

其中,f_i 为第 i 个处理单元的氮损失率

图 4 畜禽粪便清扫、堆积及处理各单元的氮损失率及最终进入农田的氮量

Figure 4 Nitrogen loss during the individual unit of cleaning, storage and treatment of manures, and nitrogen input to farmlands

果对粪污厌氧发酵单元氮素损失率作进一步修正。发酵后氮素在液相中的比例及铵态氮浓度均增加,增大了沼液后处理的技术难度及还田过程中氨挥发和径流损失的风险[76,78,89]。与固体有机肥相比,液体沼肥需要采取不同的田间运筹方式,对运输及施用设备和条件的要求更高,才能有效地降低其还田过程中的氮损失。

(4)在沼液贮存单元,其中的全氮及铵态氮含量大幅削减,导致进入农田的氮量降低了 16%~59%。从资源利用角度讲,经氧化塘或沉淀池等存放后的沼液其固体悬浮物大幅降低[78],方便采用管道运输及使用滴灌、渗灌等设备进行农田施用,可大大提高其氮素利用率[90]。从氮、磷污染负荷削减角度讲,在耕地承载能力不足的区域,采用氧化塘、人工湿地等处理模式,可显著降解沼液中的氮含量[90-91]。

(5)扣除各处理单元中损失的氮,畜禽粪便中约有 6%~80% 的氮可以还田利用,均值(43%)低于 Oenema 等的报道结果[16]。

综上所述,为实现农业和环境的可持续发展,须基于养殖场周边土地的承载力对畜禽粪便还田的风险进行评估,建立健全环境风险评价及预警机制,以此为依据发展生态型畜牧养殖业。基于前面的分析,今后在农田畜禽粪便氮负荷估算及环境风险评价时,除了考虑畜禽养殖场的规模、数量、耕地面积、粪便产生量等问题外,还应关注其清扫、存放、后处理方法、田间运筹等环节。此外,不同类型的农作物对养分的需求量不同,不同地区可以调整当地的种植结构来改变耕地对畜禽粪便承载力,使耕地能够最大限度地消纳畜禽粪便[92]。

5 降低畜禽粪便处理过程中氮损失的主要途径

畜禽粪便处理过程中以气体形式为主的氮损失,不仅降低了其氮素还田利用率,而且污染大气、危害人畜健康、腐蚀设备以及带来酸雨危害和水体富营养化[93]。有效降低畜禽粪便处理过程中氮损失,备受国内外研究者的关注。影响粪便中氮损失主要因素有:粪便类型、气候条件和管理模式。前两者受到养殖发展及地域的限制,对于减少氮损失的潜力十分有限;而粪便管理模式对于氮损失的控制非常显著[70,94-96]。

5.1 畜禽粪便清扫和堆积单元

采用干清粪方式可以显著降低粪便中的氮损失约 39%~58%[10,12]。同时,对粪污进行固液分离可有效降低后续处理中的氮损失[18-19,34]。例如,化粪池中的猪粪经固液分离后,其 NH_3 挥发减少 90%[18];而奶牛粪固液分离后存放,液体部分 NH_3 挥发减少了 4.1%,氮氧化物减少了 55.4%[19]。

在畜禽粪便临时堆积单元,保持低温[14,18-19,23]、控制通风[19,23,97-99]、增加覆盖物[43,47,65,100-102]等措施分别可使粪便中的氮损失降低 33.2%~64.5%、>12.2% 和 19.5%~33.1%。

5.2 畜禽粪便处理单元

高温好氧堆肥过程中氮素的损失主要发生在堆

肥前期，NH_3 挥发是其中最主要的损失途径，可达 41%~90%[35]。如何在堆肥温度上升阶段和高温期抑制 NH_3 的释放是控制氮损失的关键，李顺义等[102]和黄向东等[103]对此已作了综述。通过调节堆肥物料的初始特征（如 C/N 值、含水率和颗粒大小）和堆肥过程中的环境参数（如 pH、温度、通气量）、改善堆肥工艺条件（如堆肥方式、覆盖）等措施，均能显著降低畜禽粪便高温好氧堆肥过程中的 NH_3 挥发损失。通过添加化学物质（如明矾、磷酸、竹醋酸、过磷酸钙、硫酸盐、氯化镁和氯化钙等）可使 NH_3 挥发损失降低 10.0%~76.0%；通过添加物料吸附剂（如秸秆、沸石、废渣、膨润土等）可使 NH_3 挥发损失降低 23.6%~50.0%[102-103]。除了 NH_3 挥发损失，堆肥过程中氮素其他损失途径（如有机氮、氮氧化物）所占的比例为 19%~59%[25]。笔者选择 1990—2012 年间，试验条件清晰且有量化保氮效果的文献进行了汇总分析，发现：堆肥过程中覆盖[43,47,64-65]可降低 3.8%~33.1%的氮损失，添加无机盐等化学制剂[27,39,45,49-51,53-54,104-106]可降低 35.0%~81.8%的氮损失、接种微生物菌剂[25,48,60,101]可降低5.8%~41.1%的氮损失。

与高温堆肥相比，厌氧发酵可以减少粪便中氮损失约 36%；干法发酵比湿法发酵减少 10%~33%的氮损失[73-76]，同时大幅削减沼液的产生量，降低沼液还田及后处理过程中氮损失的风险[76,78,89]。

6　结语与展望

根据本研究室研究结果，结合国内外已有的研究报道，估算畜禽粪便 3 条主要处理利用途径的氮素实际入田率分别为：（1）清扫→堆积→还田（29%~80%粪便氮量，均值为 55%粪便氮量）；（2）清扫→堆积→高温好氧堆肥→还田（6%~56%粪便氮量，均值为 31%粪便氮量）；（3）清扫→厌氧发酵→沼液贮存→还田（9%~51%粪便氮量，均值为 30%粪便氮量），扣除各处理单元中损失的氮，畜禽粪便中约有 6%~80%的氮可以还田利用，均值 43%。但需要说明的是，由于畜禽粪便在清扫过程中的氮损失报道较少，而粪便出舍后至厌氧发酵前这一过程中氮的损失率未见相关报道，本文目前的估算量还有待进一步研究与完善。采用物理方法、添加化学或微生物菌剂能够有效降低畜禽粪便各处理环节的氮素损失。在今后的研究中，应加强畜禽粪便各处理环节中的保氮措施的优化，以减少氮素损失与提高畜禽粪便中氮素还田利用率。

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