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放牧家畜排泄物 N 转化研究进展

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摘要：放牧家畜排泄物氮转化是草原生态系统氮循环的关键。自 20 世纪 70 年代以来，以提高氮利用效率和减少温室气体排放为目的的家畜排泄物氮转化的研究越来越受到人们的重视。放牧家畜排泄物氮的转化研究主要包括 3 个方面：氮的矿化、硝化与反硝化，氮的氨化。家畜粪氮矿化速度慢，持续时间长；尿氮矿化速度快，持续时间短。氮矿化与家畜排泄物 C∶N 比、木质素/氮素比、木质素含量和纤维素含量呈负相关关系，而与全氮含量和水溶性氮含量呈正相关；土壤动物和微生物可以显著促进氮的矿化过程；高温和相对干燥、砂质土壤较壤土和粘土有利于氮的矿化。4～40℃氮硝化作用与温度呈正相关；硝化作用的底物和产物浓度、土壤溶液渗透压和氯化物浓度的增加对硝化作用有强烈的抑制效应；pH6.0～8.0 条件下硝化作用强度随着土壤 pH 值的升高而增加，而 pH 值高于 8.0 或低于 6.0 时硝化作用受到抑制；硝化作用与土壤氧气含量呈正相关关系，而与土壤含水量呈负相关；温暖湿润较干燥炎热的气候条件有利于硝化过程的进行。反硝化作用与土壤氧气浓度呈负相关关系，而与土壤含水量和可利用有机碳含量呈正相关；0～65℃反硝化作用强度随温度升高而增大，10～35℃条件下温度成为影响反硝化作用的关键因素；反硝化作用在 pH<4 时受到强烈抑制，6～8 时 pH 值的变化对反硝化作用的影响较小。家畜排泄物氮氨化作用与土壤 NH_4^+ 浓度、太阳辐射、温度和 pH 值呈正相关关系，而与土壤阳离子交换量(CEC)、土壤 pH 缓冲能力和土壤有机质含量呈负相关；除极度干燥外，土壤湿度对氨化作用影响较小；干燥、炎热、多风较湿润、凉爽、少风的天气有利于氨化过程的进行；氨化作用与尿斑和粪斑的植物凋落物量呈正相关关系，而与植物生物量、生长量和植被盖度呈负相关。

关键词：家畜排泄物；氮矿化；硝化作用；反硝化作用；氨化作用

Nitrogen turnover from grazing livestock excreta: a review

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Abstract: Nitrogen turnover from grazing livestock excreta is the key process in the nitrogen cycle of pasture ecosystems. Since the 1970s, many studies of nitrogen turnover from grazing livestock excreta have been conducted in order to improve nitrogen use efficiency and reduce greenhouse gas emission. Nitrogen turnover research mainly includes three related aspects: (i) Nitrogen mineralization, (ii) Nitrification and denitrification, and (iii) Nitrogen ammonification. Differences exist between the nitrogen mineralization of livestock urine and manure. The rate of manure nitrogen mineralization is very slow and continues for a long time, but for urine ,the rate is fast and is completed quickly. The factors that influence nitrogen mineralization

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mainly include excreta properties and biotic and soil variables. Negative correlations between nitrogen mineralization and C:N ratio, lignin to nitrogen ratio, lignin and fibre content of livestock excreta; and positive correlations between nitrogen mineralization and total nitrogen, water-soluble nitrogen and microbial nitrogen content of livestock excreta have been reported. Soil animals and microorganisms, high temperature, relatively dry soil and sandy soil can promote the nitrogen mineralization process. Nitrification shows significantly positive correlations with soil temperature and oxygen content, and significantly negative correlations with soil water, substrate and production content, soil osmotic pressure and chloride content. In the range pH 6.0～8.0, nitrification rate increases as pH increases, however nitrification will be inhibited if pH is higher than 8.0 or lower than 6.0. Nitrification increases under warm and wet climate conditions. Denitrification has significantly negative correlations with oxygen content, and positive correlations with soil water and available organic carbon. In the range 0～65℃, denitrification rate increases as the temperature increases. Between 10℃ and 35℃, the rate of denitrification is very dependent on temperature, often doubling with a 10℃ increase over this range. Denitrification is inhibited by strongly acidic conditions (pH<4), but soil pH has little effect on denitrification in the range pH 6～8. The presence of plants can both promote and inhibit denitrification. Nitrogen ammonification is positively correlated with soil NH_4^+ content, solar radiation, temperature, soil pH and plant litter quantity, but negatively correlated with soil cation exchange capacity (CEC), the buffering capacity of soil pH, soil organic matter content, plant biomass, plant growth yield and vegetation cover. The moisture content of the soil has little effect on nitrogen ammonification, unless the soil is so dry that urease activity is inhibited. Hot, dry, windy climate conditions favor ammonification whereas cool, moist, windless conditions inhibit ammonification.

Key words: excreta; nitrogen mineralization; nitrification; denitrification; ammonification

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放牧草原是一个复杂的生态系统。氮是草原生态系统化学元素循环中的重要元素,放牧家畜通过土壤-植物-动物系统对草原土壤氮养分施加着显著的影响[1～3]。放牧家畜对其消化的养分只是吸收利用了很小的一部分,其中60%～90%的养分又以粪尿的形式归还到草原[4],粪尿尤其是尿中存在着大量的氮,因此尿斑和粪斑成为氮转化的主要场所[2,3]。家畜排泄物除可以为土壤提供有机质和部分有机、无机氮外,有30%～65%的氮通过淋溶和气体(NH_3,NO,N_2O,N2)挥发损失掉[4,5],氮的损失不仅降低了土壤肥力而且由于淋溶(主要是NO_3^-)和气体(NH_3,NO,N_2O)的挥发,对地下水和大气环境造都成了一定程度的污染和破坏[6～8]。从全球水平看,放牧草原排放的N_2O就占到了全部N_2O排放量的10%～15%[9]。因此,对放牧家畜排泄物氮的转化进行研究具有重要的理论和现实意义[10]。放牧家畜排泄物氮的转化研究主要包括3个方面:(1)氮的矿化(这里主要指NH_4^+的形成过程,以下同)(2)氮的硝化和反硝化;(3)氮的氨化。

1 放牧家畜排泄物氮的矿化

放牧家畜主要以尿和粪的形式进行氮的归还,其中90%以上的氮为有机形态[11],只有在土壤动物和微生物的作用下转化为无机态氮,才能被植物吸收利用[12,13]。

1.1 家畜排泄物氮矿化特征

放牧家畜排泄物主要为粪和尿,由于粪、尿中有机氮的形态不同[14～16],两者氮矿化的特征存在显著差异[15,16]。

家畜粪便氮的主要矿化途径包括蛋白物质的氨化、氨基酸糖及其多聚体的氨化和核酸物质的脱氨,另外也有少量的尿素脱氨[18,19]。由于高比例的木质素[20],家畜粪便氮的矿化速率非常慢,通常要比所食入的牧草慢得多[11,21]。在家畜粪便氮矿化的前35d,粪斑中氮的浓度呈下降的趋势,但在随后的35d氮的浓度开始增加[17],这可能是家畜粪便氮矿化初期大量NH_3挥发损失的原因[22]。总的来看,家畜粪便氮矿化速率慢,持续时间长[21,22]。

家畜尿氮的矿化主要是尿素的水解脱氨途径[11]。根据Ball[28]和Vallis等人[24]的研究,家畜尿氮矿化的最初24h尿斑pH值迅速升高,其中表层土壤升高最快[24,25]。当硝化作用出现后尿斑pH值开始下降[24,25]。Sherlock和Goh[25]的研究表明,在相同环境条件下家畜尿中的尿素水解速度要比纯尿素快得多[25,26]。家畜尿斑形成的最初24h尿素水解速度最快[25,27],0～10cm土壤NH_4^+浓度达到0.1～0.25mg/g土[25,27,28],而0～2.5cm土层则高达0.5～1.0mg/g土[26]。与家畜粪相比,尿N的矿化速度快,持续时间短[27],除极度干燥或低温外,一般只需3～4.7h就可完成50%的尿素水解过程[92]。

1.2 家畜排泄物氮矿化的影响因素

根据前人的研究,家畜排泄物氮矿化的主要影响因素可以分为3类,即排泄物特性因素(内在因子)、生物因素和土壤因素(外在因子)。

1.2.1　排泄物特性　氮矿化与排泄物 C∶N 比和木质素/氮素比(L/N)呈负相关关系[29~33]。根据 Floate[11]和 Bengtsson 等人[32]的研究,家畜粪的 C∶N 比在 25∶1~30∶1 时,氮矿化初期无机氮全部被细菌固化,随着矿化进行才有部分无机氮释放;当 C∶N 比大于 30∶1 时,则持续几周没有无机氮的释放;C∶N 比小于 25∶1 时,则几周内就会出现净氮矿化。Pansu 和 Thuries[33]的研究表明,木质素/氮素比(L/N)对氮矿化的影响比气候因子更强烈。另外,全氮含量、水溶性氮含量、微生物氮含量、木质素含量和纤维素含量均对家畜排泄物氮矿化存在不同程度的影响[30,34~36]。家畜排泄物中的重金属可导致微生物群落的减少和微生物活性的降低,因此重金属含量的增加往往会降低氮的矿化速度[38]。

1.2.2　生物因素　土壤动物可以促进家畜排泄物氮的矿化[18,20,37~39]。根据 Esse 等人[37]的研究,有土壤动物参与的氮矿化速率比没有的快 38%,其中蚯蚓和食粪性动物的贡献指数达到 64%~70%。Clarholm[40]与 Woods 等人[41]研究报道,通过取食真菌和细菌,土壤线虫类动物(nematode)和原生动物(protozoa)可以将家畜排泄物中固化在真菌和细菌中的有机氮转化为矿物氮并排出体外,促进了家畜排泄物氮的转化。微生物作为有机质分解和矿化的"工程师",是影响家畜排泄物氮矿化的最重要的生物因素[42~44]。Dalal 和 Meyer[44]研究发现,家畜排泄物氮的矿化受微生物通量的影响要强于受微生物量的影响。另外,微生物呼吸强度及其过程产生的 ATP 含量对氮的矿化亦有较大影响[43]。土壤微生物种类、群落结构同样与氮的矿化有密切关系,如真菌对地表家畜排泄物的降解和氮的矿化作用要大于其他土壤微生物,而细菌对进入土壤中的氮的矿化作用则更加重要[42,43]。

1.2.3　土壤因素　家畜排泄物氮的矿化主要受土壤温度和湿度的影响,高温和相对干燥有利于氮的矿化[45,46]。根据 Stanford 和 Zaman 等人[45]的研究,土壤湿度在满足微生物生理要求的条件下,5~30℃范围内家畜排泄物氮的矿化速度随着温度的升高而加快;温度大于 5℃的条件下,在土壤永久凋萎点(permanent wilting point)和田间持水量(field capacity)间氮的矿化速度随着土壤湿度的增加而加快;土壤含水量高于田间持水量时,家畜排泄物氮矿化受到抑制,主要是因为许多土壤微生物在通气不足的条件下生长繁殖受到抑制的原因[32]。短期土壤干湿交替有利于家畜排泄物氮的矿化,主要是因为干湿交替改善了土壤通气状况,并有利于微生物群落的转化和家畜粪便的破碎[47]。在一定范围内,土壤 pH 值升高有利于氮的矿化,这归因于 pH 值升高增加了有机物质的可溶性,为微生物生长繁殖提供了大量的碳氮基质[47]。Hassink 等人[32,53]对土壤质地与家畜排泄物氮矿化关系的研究表明,砂质土较壤土和粘土更有利于氮的矿化。

2　放牧家畜排泄物氮的硝化与反硝化

硝化作用(nitrification)是指铵氧化为硝酸的微生物学过程,产物主要有 NO_3^-、NO_2^-、N_2O 和 NO[49,50]。反硝化作用(denitrification)是指硝酸还原为 N_2O、NO 和 N_2 的微生物学过程[54,57]。放牧家畜排泄物氮的硝化作用和反硝化作用与草原植物生长、草原生态系统氮素循环和环境保护关系重大[50~52]。

2.1　氮的硝化作用

放牧家畜排泄物氮矿化产生的 NH_4^+ 进入土壤后,在化能自养亚硝酸和硝酸细菌的作用下被氧化为 NO_2^- 和 NO_3^-,并伴有中间产物 N_2O 和 NO 的形成[49,50]。

2.1.1　放牧家畜排泄物氮硝化作用特征　放牧家畜排泄物氮硝化作用主要有两个过程[53,54]:

$$NH_4^+ + 3/2O_2 \rightarrow NO_2^- + 2H^+ + H_2O \quad (1)$$

$$NO_2^- + 1/2O_2 \rightarrow NO_3^- \quad (2)$$

在第一个过程中往往有中间产物 N_2O 和 NO 的形成[49,50]。硝化过程由于产生 2mol H^+ 而使粪斑和尿斑 pH 值下降,产生一定程度的酸化现象[22,55]。Haynes 和 Williams[22]研究报道,随着尿斑 pH 值下降土壤溶液中离子强度显著升高,其中 Ca^{2+} 离子最明显,Mg^{2+} 离子次之。家畜尿中的尿素水解在所有季节 3d 内即可完成,但硝化作用一周后才开始明显,存在明显的时滞现象[56,57]。家畜尿斑形成一周后 0~2.5cm 土壤 NO_2^- 浓度达到 45μg/g 土,但 NO_3^- 浓度很低[24],主要是尿斑形成初期高浓度的 NH_4^+ 和高 pH 值不利于氮硝化作用第 2 个过程进行的原因[58]。随着硝化作用的进行,土壤 NH_4^+ 浓度和 pH 值下降,家畜尿斑形成 14d 后 0~2.5cm 土壤 NO_2^- 浓度显著下降,NO_3^- 含量开始明显增加[59]。

2.1.2　放牧家畜排泄物氮硝化作用的影响因素　温度是影响家畜排泄物氮硝化的重要因素[54,58,60,62]。Holland 和 During[56]报道,土壤温度 7.5~10℃时家畜尿氮的硝化作用非常缓慢,需要 60d 才能完成;土壤温度 15℃时硝化作用明显加快,只需 30d 就可完成。根据 Whitehead[61]研究,低温对硝化作用 NO_3^- 的形成过程影响更大,因此低温条件下粪斑和尿斑往往出现 NO_2^- 积累现象。Thomas 等人[54]报道,夏季家畜粪斑和尿斑的 NO_3^- 含量显著高于春、秋、冬季,可占土壤全部矿物氮的 70%~80%,而春、秋、冬季只占 25%左右。

底物和产物浓度的升高均对硝化过程产生抑制作用[63,64]。尿斑和粪斑 NH_4^+ 浓度在 0.1~1.0mg(N)/L 时硝化作用开始受到抑制,其中第 2 个过程受影响较大[24,56],这种抑制作用与土壤 pH 值有关,pH 值越高抑制效应越明显[58]。Aleem 等人[64]和

Anthonisen 等人[63]研究发现，NH_4^+ 对硝化过程的抑制效应主要是 NH_4^+ 产生的 NH_3 对硝化细菌有毒害作用。NO_2^- 浓度在 0.22～2.8mg(N)/L 时开始对硝化过程产生抑制作用，其中第 2 个过程更明显[63]，高浓度的产物主要是抑制了亚硝酸菌和硝酸菌的生长[57]。

在一定范围内，硝化作用与尿斑和粪斑土壤溶液的渗透压呈负相关[57,65]。高土壤溶液渗透压主要是对硝化细菌产生了 3 个方面的作用：①加大了细菌生长的时滞时间，②降低了细菌的生长速率，③减少了细菌细胞的合成数量[66]。许多研究表明，高浓度的氯化物对硝化过程有明显的抑制作用[57,67,68,70]。Darrah[69]研究报道，氯化物主要产生 3 个方面的效应：①直接对硝化细菌产生毒害作用，②提高土壤溶液的渗透压，③降低土壤溶液的 pH 值。氯化物对硝化作用的影响与土壤 pH 值有关[57,70]，土壤 pH 值下降氯化物的抑制作用增强，pH 值 4.9～5.5 时抑制效应最大；pH 值升高氯化物的抑制作用减弱，pH 值 6.0～6.2 时抑制作用显著下降或消失。

家畜排泄物氮硝化的适宜土壤 pH 值为 6.0～8.0[71,72]，在此范围内硝化作用与 pH 值呈正相关[63,73]。根据 Paul 和 Clark[73]研究，土壤 pH 值低于 6.0 硝化作用受到抑制，低于 4.5 则硝化作用基本停止，低土壤 pH 值主要是抑制了硝化细菌的生长和酶活性，并使氯化物对硝化过程的抑制作用增强。土壤 pH 值高于 8.0 时硝化作用同样受到抑制，其中第 2 个过程更明显，因此高 pH 值条件下尿斑中出现 NO_2^- 的积累现象[24,81]。根据 Monaghan 和 Barraclough[57]研究，高土壤 pH 值主要是促进了 NH_3 的形成，加剧了对硝化细菌的毒害作用。

硝化作用是需氧过程，氧气对硝化细菌（亚硝酸菌和硝酸菌）是绝对必需的[57]。Smith 和 Arah[75]研究报道，硝化作用的氧气含量临界值为 10%～17%，土壤氧气含量高于临界值则促进硝化过程，低于临界值则产生抑制作用。土壤水分张力 −0.1～−1.5 MPa 为硝化作用最适的水份条件[73,76]，低于或高于此临界值，都会抑制硝化过程[76]。Berendse 等人[90]研究了家畜粪斑和尿斑土壤地下水位与硝化作用间的关系，土壤地下水位升高 25cm，氮硝化量减少 60%～76%。一般情况下，土壤水分含量超出田间持水量则硝化作用受到抑制[45]，Monaghan 和 Barraclough[79]研究认为，土壤含水量对硝化作用的影响往往与土壤质地有关。

气候对家畜排泄物氮的硝化也有一定影响。根据 Thompson[80]和 Ball[28]等人的研究，温暖湿润的气候有利于硝化作用的进行，尿斑形成的 3～5 周有高达 70%～80%的氮转化为 NO_3^-；而在干燥炎热的气候条件下，尿斑形成的 41 d 只有 20%～23%的氮转化为 NO_3^-[23]。

2.2 氮的反硝化作用

反硝化作用(denitrification)是指硝酸还原为 N_2O、NO 和 N_2 的微生物学过程[81]。土壤通气状况、水分含量、温度和 pH 值是影响反硝化作用的主要因素[7,77,82]。

2.2.1 放牧家畜排泄物的反硝化作用特征 反硝化作用一般在厌氧环境条件下进行，在反硝化细菌还原酶作用下顺次经过：$NO_3^- \rightarrow NO_2^- \rightarrow NO \rightarrow N_2O \rightarrow N_2$ 系列还原过程[7]。根据 Haynes 和 Sherlock[82]研究，反硝化作用存在明显的时滞现象，尿斑形成 25d 只有 0%～2%的氮发生反硝化作用。时滞过后反硝化作用强度明显加大，很短时间内就可完成反硝化过程[81]。反硝化过程 NO 产生量很少，主要是 NO 还原酶活性比亚硝酸还原酶活性高的原因[7]。不同环境条件下 N_2O : N_2 比存在较大差异，高浓度 NO_3^- 和低 pH 值[77,86]条件下，N_2O : N_2 比增大；而随着土壤通气不足、可利用有机 C 含量增加和温度升高，N_2O : N_2 比下降[82,87]。

2.2.2 家畜排泄物氮反硝化作用的影响因素 大多数反硝化作用在厌氧的条件下进行，土壤通气状况和水分含量对反硝化过程存在显著影响[77,82,88]。Pilot 等人[84]研究报道，家畜排泄物反硝化作用的临界充气孔隙度为 11%～14%，高于此临界值反硝化作用受到抑制。Smith 和 Arah[75]研究了家畜尿斑反硝化作用与土壤氧气含量间的关系，氧气浓度低于 4%～17%时反硝化作用强度显著增大，而高于 4%～17%时则明显受阻。实际上，土壤氧气含量主要受土壤含水量的影响和调控，根据 Aulakh 等人[77]和 Knowles[82]研究，尿斑和粪斑 50%～70%田间持水量时反硝化作用强度非常小，100%田间持水量时反硝化作用开始明显，而 350%田间持水量时反硝化作用强度显著增大。土壤充水孔隙度(WFPS)比含水量更能很好的反映土壤水分与土壤通气状况和反硝化作用间的关系[78]。根据 Aulakh 等人[77]研究，反硝化作用的土壤充水孔隙度(WFPS)的临界值为 65%～90%，低于此临界值反硝化作用受到抑制。Ryden 等人[89]研究了几种不同质地土壤的水分和氧气含量与反硝化作用的关系，发现这些因素并不明显反映反硝化作用的差异，他们认为土壤质地可能是影响家畜排泄物反硝化作用的关键。

温度和土壤 pH 值是影响家畜排泄物反硝化作用的重要因素。反硝化可以在 0～75℃范围内进行，但 10℃以下时反硝化作用强度显著降低[86]。Knowles[82]对家畜尿斑反硝化作用与温度关系的研究表明，10～35℃条件下，反硝化速率主要决定于温度因素，温度每升高 10℃反硝化速率增加 2 倍。反硝化速率一般在 65℃时达到最高，然后随着温度的升高而下降[77,90]。反硝化作用与土壤 pH 值密切相关，根据 Firestone[86]的研究，土壤 pH<4 反硝化作用受到强烈抑制，6～8 时反硝化作用强度受土壤 pH 值影响较小，高于 8 则反硝化作用强度显著降低。Tiedje[91]研究了家畜尿斑反硝化作用的产物与土壤 pH 值的关系，pH 值 6.7

时 N_2O 为次要产物，随着 pH 值降低 N_2O 的比例增大，pH 值降至 5.2 时 N_2O 很快（3min）成为主要产物。

土壤可利用有机碳含量对家畜排泄物反硝化作用影响显著[92]，主要是可利用有机碳作为反硝化细菌生长的基质和呼吸作用的底物而直接影响反硝化细菌生长繁殖的原因。另外，可利用有机碳含量的增加还可以促进其它微生物组织的生长繁殖，该过程需要消耗大量氧气，因而有利于土壤厌氧环境的形成[86]。植物对反硝化过程既有促进作用又有抑制效应，两种效应的强度主要决定于土壤理化特性和植物生长状况[83,87,93]。

3　放牧家畜排泄物氮的氨化作用

自 19 世纪 50 年代以来，大气中 NH_3 含量增加了 50%～55%，其中家畜排泄物氮的氨化作用是主要来源之一[94]。大气 NH_3 含量的增加对生态环境产生了显著影响[94,95]。

3.1　放牧家畜排泄物氮的氨化作用特征

放牧家畜排泄物氮的氨化作用是大气 NH_3 含量增加的主要原因[94]。由于氮的含量及其组分的差异，家畜粪、尿氮的氨化作用特征有较大不同。粪氮氨化作用慢、持续时间长[97,98]。根据 MacDiarmid 和 Watkin[99]研究，放牧家畜粪便排放的第 1 周 NH_3 产生速度相对较快，第 13 天粪中的氮有 4.7%以 NH_3 的形式损失掉。家畜尿氮氨化作用快、持续时间短[98]。Vallis 等人[24]研究发现，家畜尿斑形成的最初 24h 内 NH_3 的流量以很快的速度增长，然后又缓慢下降，8～14d 后基本再没有 NH_3 的产生。总的来看，家畜排泄物氮氨化作用先快后慢，根据 Sommer[100]和 Van der Molen 等人[97]研究，这主要是尿斑和粪斑形成初期 NH_4^+ 浓度和 pH 值较高而后随着硝化作用进行而降低的原因。

3.2　放牧家畜排泄物氮氨化作用的影响因素

家畜排泄物 NH_3 的形成过程主要受土壤理化性状的影响[101～103]。粪斑和尿斑溶液中 NH_4^+ 的浓度和土壤 pH 值是影响氨化作用的关键因素[104,105]，一般情况下，NH_4^+ 浓度和土壤 pH 值越高越有利于氨化作用的进行[103,105]。土壤阳离子交换量（CEC）与氨化作用存在显著的负相关关系（$R=-0.834$）[105,106]，主要是土壤阳离子交换量（CEC）越高，土壤溶液中 NH_4^+ 浓度越低的原因[106]。土壤有机质与氨化作用过程有关，有机质含量越高越不利于 NH_3 的形成[107]，根据 O'Toole 等人[105]和 Stevens 等人[108]研究，土壤有机质主要是通过影响土壤 pH 缓冲能力和阳离子交换量（CEC）而作用于氨化过程。土壤温度对氨化作用影响明显，根据 Lockyer 和 Whitehead[74]研究报道，家畜粪斑和尿斑形成的前 3d，0～3cm 土壤温度与氨化作用存在显著的正相关关系（$R=0.862$），主要是温度的升高促进了有机氮的矿化和尿酶的活动，加快了 NH_4^+ 的形成和扩散[110]。除土壤极度干旱外，土壤湿度对家畜排泄物（尤其是尿）氨化作用过程影响不明显[111]。

除土壤环境外气候条件也是影响家畜排泄物氨化作用的重要因素[96,112]。气温对 NH_3 的形成过程影响较大[24,109]。根据 Ryden 等人[113]研究，平均气温 16℃时，家畜尿中的氮有 22%转化为 NH_3，而在 8℃时则只有 10%。太阳辐射强度与氨化作用呈显著的正相关关系[114,115]，主要是太阳辐射强度的提高增加了气温和土壤温度，同时加快了粪斑和尿斑水分的蒸发而使 NH_4^+ 浓度升高的原因。Reynolds 和 Wolf[116]研究报道，大气相对湿度对家畜排泄物的氨化作用过程影响较小，但当土壤极度干旱时相对湿度的增加显著促进了 NH_3 的形成，这可能是湿度增加有利于氮矿化的原因[117]。干燥、炎热、多风的天气易于家畜排泄物 NH_3 的产生和排放，而湿润、凉爽、少风的天气则不利[91,112]。降雨影响氮的氨化作用过程[118,119]，其影响程度主要决定于降雨量[118]。

根据 Fenn 等人[120]和 Nelson 等人[121]研究，家畜尿斑和粪斑的植物凋落物量与氨化作用呈显著的正相关关系，主要是植物凋落物为尿酶和其他微生物提供了良好的活动界面[122]，并降低了粪尿与土壤的接触面积而减少了 NH_4^+ 因土壤阳离子交换损失的原因[97]。绿色植物叶片和根系可以吸收同化 NH_3，因此，植物生长量、生物量和群落盖度与 NH_3 的排放量间存在着一定的负相关关系[97]。

4　家畜排泄物氮矿化、硝化和反硝化、氨化间的关系

家畜排泄物氮矿化、硝化和反硝化、氨化间存在促进或抑制作用关系。家畜排泄物氮矿化由于产生大量的 NH_4^+ 和 OH^-，而加速了氮的氨化作用过程[103,105]，但抑制了硝化作用和反硝化作用[24,109]。而随着氨化作用、硝化作用和反硝化作用的进行，土壤 pH 值下降，氮矿化过程开始缓慢[22,55,47,123,74]。氨化作用由于降低了 NH_4^+ 浓度和土壤 pH 值[74]，因而有促进硝化和反硝化过程的作用[63,64,58,86]。根据 Whitehead 的研究[123]，硝化和反硝化过程对氮氨化作用有抑制效应，主要是硝化和反硝化作用降低了 NH_4^+ 浓度和土壤 pH 值的原因。

5　研究展望

虽然对放牧家畜排泄物氮转化的研究已有 30 多年的历史，但仍有许多领域的研究亟待加强和完善[2,12,17,123]：（1）氮矿化-固定过程的动态作用机制；（2）家畜排泄物氮矿化潜力；（3）硝化过程 N_2O 和 NO 的排放及土壤质地的作用机制；（4）有机态氮的淋溶损失过程；（5）氨化作用的抑制机制；（6）反硝化过程可利用有机碳的作用机制及反硝化作用在表土和底土的发生过程。

为提高草地氮素养分的利用效率和减少有害气体排放,今后应重点加强以上 6 个方面的研究。

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