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Effects of nitrogen fertilization on forage production, animal performance, and greenhouse gas emissions in tropical pastures: A systematic review

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ABSTRACT

This systematic review aimed to synthesize evidence on the effects of nitrogen (N) fertilization on forage production, animal performance, and greenhouse gas emissions in tropical pastures. The research question was developed based on the PICOS strategy. A total of 84,629 documents were retrieved from six databases, of which 34 studies met the inclusion criteria due to their methodological robustness. Most studies were conducted under grazing conditions (69.7%), using *Brachiaria brizantha* (52.9%) and *Panicum maximum* (26.5%). Urea (53.2%) and ammonium nitrate (25.5%) were the most evaluated N sources, with application rates ranging from 0 to 1000 kg ha^{-1} , often split into three applications. Nitrogen use increased stocking rate (157.7%), gain per area (189.4%), and average daily gain (31.0%) when application rates rose from 0 to 300 kg ha^{-1} . Overall, N fertilization has potential to improve forage productivity and animal performance in tropical pastures; however, responses vary depending on rates, sources, and experimental conditions. Splitting N rates (20–60 kg ha^{-1}) and synchronizing applications with plant demand are effective strategies to reduce NH_3 and N_2O losses, enhance fertilizer use efficiency, and mitigate environmental impacts. Future research should focus on evaluating the effects of different N sources and doses on soil CO_2 and CH_4 emissions, enteric CH_4, and C/N dynamics within the soil–plant–animal system, as well as expanding studies to other forage and animal species representative of tropical grazing systems.

1. Introduction

Nitrogen (N) is an essential nutrient for enhancing the growth and persistence of tropical forages (Pereira et al., 2022). Nitrogen deficiency, often associated with other nutrients such as phosphorus (P) and potassium (K), combined with inadequate grazing management, is one of the main causes of reduced pasture productivity and one of the leading factors contributing to pasture degradation (Pasquini Neto et al., 2025).

In tropical regions, the use of N in pastures is fundamentally important, as most of the grasses employed in production systems have medium to high nutrient requirements due to their elevated growth rates, productivity, and nutrient extraction capacity. This is particularly true for grasses of the genera *Panicum, Pennisetum, Cynodon*, and *Brachiaria* (Pereira et al., 2022).

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The application of N in tropical pastures has proven to be an essential practice for intensifying food production (Da Silva et al., 2024), due to the significant increases it promotes in forage production and animal performance (Euclides et al., 2022; Galindo et al., 2017; Oliveira et al., 2020). This practice plays a fundamental role in meeting the global demand for increased food production (FAO, 2019; Food and Agriculture Organization of the United Nations, 2023), driven by the growth of the world population. Some studies suggest that the rational use of N in tropical pastures can optimize land use, reduce the need for deforestation to expand livestock areas, and improve nutrient use efficiency (Bastidas et al., 2024).

However, despite these agronomic and productive benefits, nitrogen fertilization has important environmental implications that need to be considered. The same processes that enhance plant growth and productivity can also lead to nitrogen losses to the atmosphere and soil, particularly in the form of ammonia (NH_3) volatilization and nitrous oxide (N_2O) emissions. These nitrogen-derived emissions connect pasture management directly to broader environmental concerns, as N_2O is one of the most potent greenhouse gases contributing to global warming. Understanding the balance between the productive benefits of nitrogen use and its environmental consequences is therefore essential for developing sustainable pasture systems in tropical regions.

Global warming is characterized by a significant rise in the planet's average temperature, which accelerates the melting of polar ice caps, causes sea-level rise, leads to species extinction, and alters climatic conditions (IPCC, 2007). These phenomena are closely related to the emission of greenhouse gases (GHGs) into the atmosphere, mainly carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N2O) (Abreu et al., 2024). Greenhouse gases exist in the atmosphere in varying concentrations, with CO_2 accounting for approximately 62%, CH_4 for 16%, and N_2O for 7%. These gases are expressed in terms of CO_2 equivalents or Global Warming Potential (GWP), with CO_2 assigned a GWP of 1, CH4 a GWP of 28, and N_2O a GWP of 265, the latter two having greater pollution potential (IPCC, 2019). These emissions result from human activities in the energy, agricultural, and industrial sectors, as well as from waste and land use changes (Abreu et al., 2024).

In industrialized countries, most emissions originate from sectors such as industry, transportation, and power generation (Xin et al., 2022). In contrast, in developing countries, the largest emissions stem from agricultural activities (Houzer and Scoones, 2021) mainly related to enteric fermentation, waste management (urine and feces), nitrogen fertilizer application, and soil emissions (Cardoso et al., 2020; Mazzetto et al., 2015).

The combined effects of nitrogen fertilization on forage production, animal performance, and GHG emissions remain underexplored, particularly in tropical regions of South and Central America (Morais et al., 2013; Rodrigues et al., 2022). Current experimental protocols often focus on assessing only one or two of these components (Almeida et al., 2024; Gurgel et al., 2021), resulting in informational gaps and fragmented conclusions.

Given this context, the present study aims to systematically review and synthesize the existing scientific evidence on the effects of nitrogen fertilization in tropical pastures, integrating findings related to forage production, animal performance, and greenhouse gas emissions. This literature-based synthesis seeks to identify knowledge gaps and guide future research toward more sustainable and integrated pasture management strategies.

2. Methods

This is a Systematic Review (SR) of the literature, conducted and reported in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines (Page et al., 2021). An SR is a type of literature review that employs predefined strategies to minimize bias in the identification and analysis of data from previously published original articles (Moher et al., 2015).

2.1. Review protocol and guiding question

To conduct this SR, a review protocol was previously developed, tested, and refined to ensure a rigorous, high-sensitivity procedure for searching and extracting articles (Appendix A). The review protocol was registered and is available on the Open Science Framework platform at the following link: https://osf.io/ujt7q/

A high-sensitivity search strategy was used to address the research objective. The guiding question was formulated using the PICOS strategy, where the population (P) was tropical forage grasses, the intervention (I) was nitrogen fertilization (N sources), the comparison (C) was the use of different nitrogen rates, and the outcome (O) was forage production, animal performance, and greenhouse gas emissions. For the study design (S), only experimental studies were included. Therefore, the question addressed in this review is: “Based on existing studies, what are the effects of nitrogen fertilization (N sources and rates) on forage production, animal performance, and greenhouse gas emissions in tropical pastures?”

Due to the absence of a thesaurus or standardized set of descriptors for Animal and Plant Sciences, a peer review of previously published scientific articles was conducted to ensure the use of sensitive search terms for identifying relevant studies. This analysis focused on extracting terms related to nitrogen fertilization, forage production, animal performance, and greenhouse gas emissions, as available in the titles, abstracts, and keywords of the studies. This method is often used in research of this nature in this field of study (Costa et al., 2021; Freitas et al., 2025; Monteiro et al., 2025). The selected terms served as the basis for the construction of the cross-references used in this review.

2.2. Eligibility criteria

The studies included in this review were research articles, available in full in five databases and one electronic library, formatted as well-designed experimental studies, in any language, with no time restrictions. When necessary, the studies were translated from English into Portuguese using the DeepL online tool (https://www.deepl.com/pt-BR/translator). Documents retrieved in the form of editorial letters, letters to the editor, expert opinions, reviews, correspondence, book chapters, theses and dissertations, abstracts, lectures, and books were excluded from the search.

Studies in which nitrogen fertilization was derived from organic sources or exclusively from nitrogen-fixing microorganisms, studies involving native and/or temperate forages, and studies with grass-legume intercropping without nitrogen fertilization treatment that evaluated only the legume as a source of N were also excluded.

Studies that did not present measurement units for the variables and/or in which the equations provided did not correspond to the values reported in the plots were excluded. Studies lacking a description of the evaluation, analysis, or acquisition methods for study variables were also excluded.

Studies evaluating the residual effects of N rates were included. Studies that lacked certain important information, such as soil type, N source, or cultivar, but did not present other methodological flaws, were also considered.

2.3. Information sources

For high-sensitivity electronic searches, the following databases were used: SCOPUS (Elsevier), Web of Science (main collection), Springer Link, Science Direct (Elsevier), SciELO, and the Cab Direct electronic library. Searches were conducted between November 1 and 23, 2023. Access to information sources was provided through the CAPES Journal Portal, via proxy from the Federal University of Mato Grosso do Sul (UFMS, Brazil).

2.4. Search strategies

For the peer-reviewed searches in the databases and the electronic library, Boolean descriptors and operators were used in five cross-references (Table 1). These cross-references were constructed with the aim of identifying articles that answered the research guiding question.

In the five cross-references established based on the descriptors, cross-reference "A = 1# AND 2# AND 4#" was intended to identify studies that evaluated the effects of N fertilization on greenhouse gas emissions, regardless of variables related to forage production or animal performance. Cross-reference "B = 1# AND 2# AND 5#" aimed to identify studies that associated N fertilization with animal performance, without requiring the inclusion of pasture-related variables. Cross-reference "C = 1# AND 2# AND 3# AND 4#" was directed at the selection of articles that simultaneously integrated N fertilization, forage production, and animal performance. Cross-reference "D = 1# AND 2# AND 3# AND 5#" encompassed studies that jointly addressed N fertilization, forage production, and greenhouse gas emissions. Finally, cross-reference "E = 1# AND 2# AND 3# AND 4# AND 5#" included broader investigations that simultaneously considered forage production, animal performance, and greenhouse gas emissions in tropical pastures. These cross-references are illustrated in Fig. 1.

Given the limited number of descriptors allowed per search in some databases, certain cross-references were adjusted for searches conducted in Science Direct, Cab Direct, and Springer. Once the cross-referencing was completed, searches were performed in the databases by two previously trained reviewers (HRS and FFSR).

The selection of articles was carried out independently by the same reviewers who performed the searches. During this phase, each reviewer read the titles, abstracts, and keywords and independently included or excluded articles based on the established eligibility criteria.

After the initial evaluation of all articles, the reviewers met to resolve any disagreements through consensus following an analysis of the discordant articles. Subsequently, the full texts of the selected articles were read and examined thoroughly, with final inclusion based on the eligibility criteria. Microsoft Excel® software was used during all screening stages. Duplicate articles were considered only once.

2.5. Data collection processes

A data extraction form was developed in Microsoft Excel® to gather information from the relevant articles. The form included the following information: publication identification (article title, authors, country where the study was conducted, language and year of publication, and DOI), journal name, methodological details (duration of the experimental evaluation, treatments, number of replicates, N source used, nitrogen fractionation, grazing method, pasture height control, number of test animals, animal categories, breed or breed standard, and initial animal weight), variables analyzed (pasture productive traits, chemical composition, animal performance metrics, CO_2, CH_4, N_2O, and NH_3 emission variables, and C and N contents), and the results obtained.

All results related to the variables were tabulated using Microsoft Excel®. The online version of the Plot Digitizer software (https://plotdigitizer.com/app) was used to extract data presented in graphical form in the study by Homem et al. (Homem et al., 2021), data related to forage production. During the eligibility and inclusion phase, author contact was required when full-text articles were not accessible through the CAPES Journals Portal. Communication was established via e-mail and/or *ResearchGate*.

2.6. Assessment of methodological quality and risk of bias

The quality of the studies was assessed using the Critical Appraisals Skills Program (CASP, 2018) instrument for experimental studies (CASP Randomized Controlled Trial Standard Checklist), which consists of 11 questions addressing study design, methodology, and results.

Table 1
Descriptors and single cross-reference performed in the high-sensitivity search for the systematic review.

Acronym	Descriptors
Population (P)	("Brachiaria" OR "Urochloa" OR "Panicum maximum" OR "Megathyrsus" OR "Cynodon" OR "Andropogon" OR "Pennisetum" OR "Cenchrus" OR "Paspalum" OR "Warm-climate grasslands" OR "Tussock grass" OR "Bunchgrass" OR "Creeping grass" OR "Tropical pastures" OR "C4 Forage grasses" OR "Tropical grasslands" OR "Tropical grasses" OR "Tropical forage grasses" OR "Tropical grass" OR "Brachiaria grass" OR "Tropical forage" OR "Tropical-climate grasses")
AND	
Intervention (I) and Comparison (C)	**2#** ("Nitrogen fertilizer" OR "Nitrogen Fertili*er levels" OR "Urea" OR "Nitrogen fertili*ation" OR "Ammonium sulfate" OR "Ammonium nitrate" OR "Nitrogen effect" OR "Synthetic fertilizer" OR "Nitrogen rate" OR "Nitrogen doses" OR "Nitrogen requirement" OR "N rates" OR "Nitrogen fertilized" OR "Efficiency and nitrogen" OR "Pasture fertilized" OR "Mineral nitrogen" OR "Nitrogen levels" OR "Rates of nitrogen" OR "Nitrogen fertilization in top dressing" OR "Different nitrogen fertilization" OR "Nitrogen fertilization management" OR "Nitrogen fertilizer management" OR "Nitrogen fertilization strategies" OR "Nitrogen-fertilized" OR "Nitrogen management strategies" OR "Nitrogen fertilizers" OR "Nitrogen efficiency use" OR "Nitrogen top dressing" OR "Nitrogen supply" OR "Fertilized with nitrogen" OR "pasture fertilization" OR "Different n sources" OR "Different n doses" OR "N sources" OR "Nitrogen application rate" OR "Nitrogen efficiency" OR "Nitrogen efficiency use" OR "N fertilizer" OR "Increasing nitrogen rates" OR "Fertilized with nitrogen" OR "Nitrogen fertilization application" OR "Management of nitrogen fertilization" OR "Urea fertilizer" OR "Nitrogen")
AND	
Outcome (O)	**3#** ("Forage mass" OR "Forage accumulation" OR "Accumulation rate" OR "Biomass" OR "Forage production" OR "Number tillers" OR "Tillering" OR "Dry Mass" OR "Biomass" OR "Sward" OR "Herbage" OR "Herbage mass" OR "Herbage accumulation" OR "Tiller population" OR "Grass" OR "Dry matter" OR "Plant height" OR "Pasture" OR "Sward height" OR "Dry matter production" OR "Cutting number" OR "Growth" OR "Accumulation" OR "Harvest" OR "Forage allowance" OR "Aftermath" OR "Residue" OR "Senescence" OR "Canopy" OR "Rate of accumulation" OR "Structural characteristics" OR "Tiller population density" OR "Forage accumulation rate" OR "Grass forage mass" OR "Biomass accumulation" OR "Forage yield" OR "Forage nutritive value" OR "Cutting intervals" OR "Cutting heights" OR "Tillering dynamics" OR "Chemical composition" OR "Growth dynamics" OR "Morphogenetic" OR "Morphogenic" OR "Morphogenesis" OR "Stability of tiller population" OR "Agronomic performance" OR "Morphological components" OR "Biomass production" OR "Growth" OR "Tillering capacity" OR "Continuous stocking" OR "Stocking density" OR "Grazing pressure" OR "Intermittent stocking" OR "Rotational stocking" OR "Grazing intensity" OR "Grazing management" OR "Forage intake" OR "Paddock" OR "Grazing system" OR "Period of occupation" OR "Stocking period" OR "Grazing intensities" OR "Grazing intensity" OR "Grazing management" OR "Grazing efficiency" OR "Grazing system" OR "Herbage intake" OR "Canopy structure" OR "Sward structure" OR "Defoliation intensity" OR "Defoliation strategies" OR "Defoliation patterns" OR "Defoliation dynamics" OR "Light interception" OR "Leaf area index" OR "Canopy height" OR "Sward height" OR "Pasture height" OR "Grazing cycles" OR "Herbage growth rate" OR "Herbage accumulation rate" OR "Morphological composition" OR "Cutting heigh" OR "Average grazing interval" OR "Mass production" OR "Biomass components" OR "Growth index" OR "Daily forage accumulation" OR "Tillers" OR "Root mass" OR "Herbage allowance" OR

(*continued on next page*)

Table 1 (*continued*)

Acronym	Descriptors
	"Shoot dry matter" OR "Root dry matter" OR "Leaf dry matter") **4#** ("Animal performance" OR "Sheep" OR "Ruminant" OR "Ruminant" OR "Beef steers" OR "Meat sheep" OR "Cattle" OR "Dairy cattle" OR "Cow" OR "Dairy cows" OR "Dairy cattle" OR " Lambs" OR "Beef cattle" OR "Performance, animal" OR "Production, animal" OR "Animal responses" OR "Weight gain" OR "Average daily gain" OR "Stocking, rate" OR "Live weight gain" OR "Milk production" OR "Livestock performance" OR "Steer" OR "Steers" OR "Heifer" OR "Heifers" OR "Bos taurus" OR "Bos indicus" OR "Cattle production" OR "Ovis aries" OR "Goat" OR "Gain per hectare") **5#** ("Greenhouse gas" OR "Methane emissions" OR "Nitrous oxide emissions" OR "Carbon dioxide emissions" OR "Greenhouse gas balance" OR "Carbon footprint" OR "CH4" OR "CO2" OR "N2O" OR "Methane production" OR "Nitrous oxide" OR "Greenhouse gas flux" OR "N2O flux" OR "CH4 flux" OR "CO2 flux" OR "N2O emissions" OR "CH4 emission factor " OR "N2O emission factor" OR "Carbon Dioxide" OR "Ammonia emission" OR "Soil methane" OR "CH4 fluxes" OR "CO2 fluxes" OR "N2O fluxes" OR "Nitrous fertilizer" OR "Ammonia volatilization" OR "NH3 losses" OR "IPCC" OR "Climate Changes" OR "Methane" OR "Ammonia" OR "Enteric methane" OR "GHG" OR "Nitrogen balance" OR "Enteric CH4" OR "Methane production" OR "Soil carbon stocks")
AND	
Study design (S)	Experimental studies

The risk of bias in the studies included in the final sample of this systematic review was evaluated using the Joanna Briggs Institute (JBI) critical appraisal tool for controlled trials, as described by Barker et al. (Barker et al., 2023). The risk of bias was considered low due to the objectivity of the reported results.

2.7. Presentation of results

To optimize the interpretation of the results, the data of the variables collected during extraction were subjected to frequency analysis.

3. Results

3.1. Selected studies

The search identified 84,629 documents, of which 66,976 were scientific articles. Of these, 54 articles were considered potential data sources, and 34 studies were deemed eligible and included due to their methodological robustness for data extraction (Fig. 1). All selected studies presented a high level of evidence, as they were individual investigations employing well-designed experimental layouts. The remaining 20 articles were excluded for various reasons, including the absence of units in response variables, incomplete description of variables not detailed in the methodology, exclusive evaluation of N fertilization from organic sources, experiments involving more than one forage species (temperate and tropical) in the same area, treatments combining multiple fertilizers (NPK), among other reasons detailed in Fig. 2.

3.2. Profile of the studies

Thirty-four articles published between 2004 and 2023 were retrieved, with 61.76% published in the last five years (Fig. 3). The studies were conducted in Brazil (31), Costa Rica (1), Honduras (1), and the Dominican Republic (1) (Fig. 4). Among the total, 76.5% were published in English, 17.6% in Portuguese, 2.9% in Spanish, and 2.9% were available in both English and Spanish (Fig. 5 A e B).

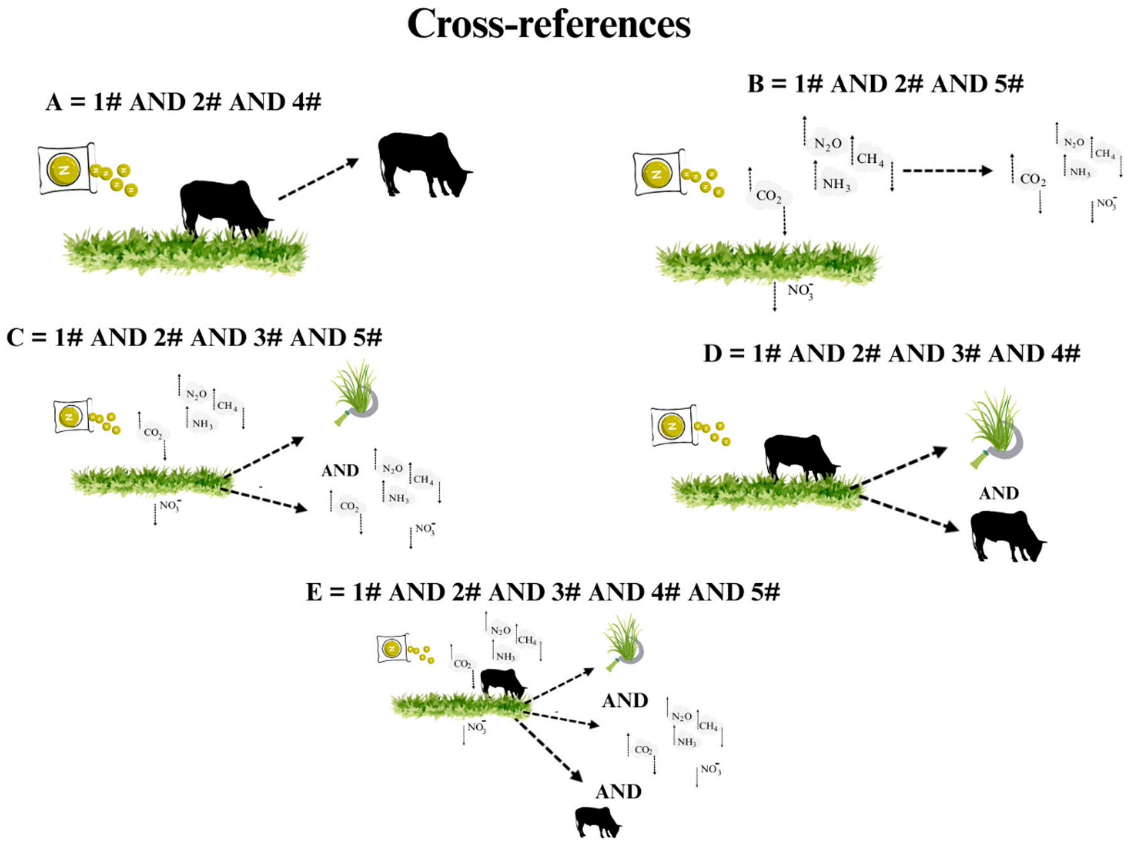
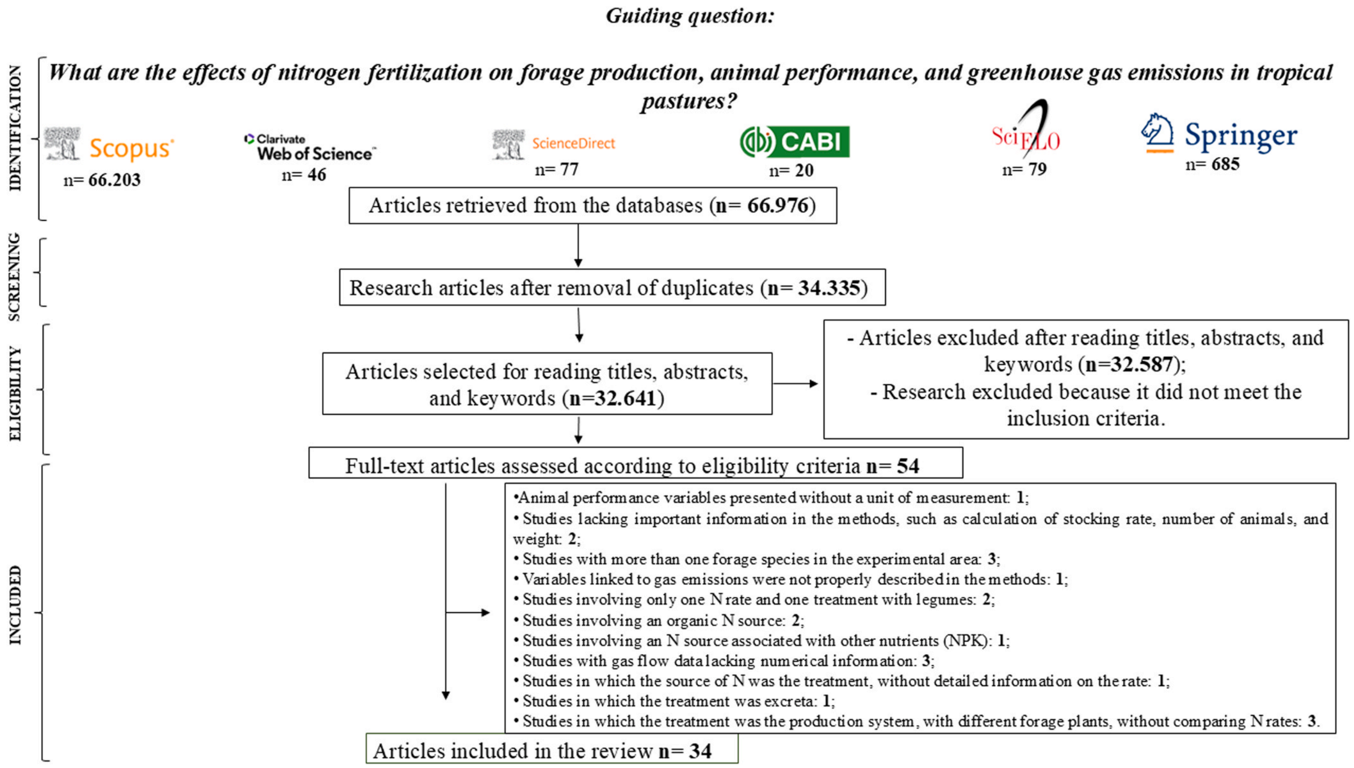


Fig. 1. Illustration of strategies for selecting and capturing studies based on cross-references.



- Animal performance variables presented without a unit of measurement: **1**;
- Studies lacking important information in the methods, such as calculation of stocking rate, number of animals, and weight: **2**;
- Studies with more than one forage species in the experimental area: **3**;
- Variables linked to gas emissions were not properly described in the methods: **1**;
- Studies involving only one N rate and one treatment with legumes: **2**;
- Studies involving an organic N source: **2**;
- Studies involving an N source associated with other nutrients (NPK): **1**;
- Studies with gas flow data lacking numerical information: **3**;
- Studies in which the source of N was the treatment, without detailed information on the rate: **1**;
- Studies in which the treatment was excreta: **1**;
- Studies in which the treatment was the production system, with different forage plants, without comparing N rates: **3**.

Fig. 2. Flowchart illustrating the selection process for the final sample of the Systematic Review.

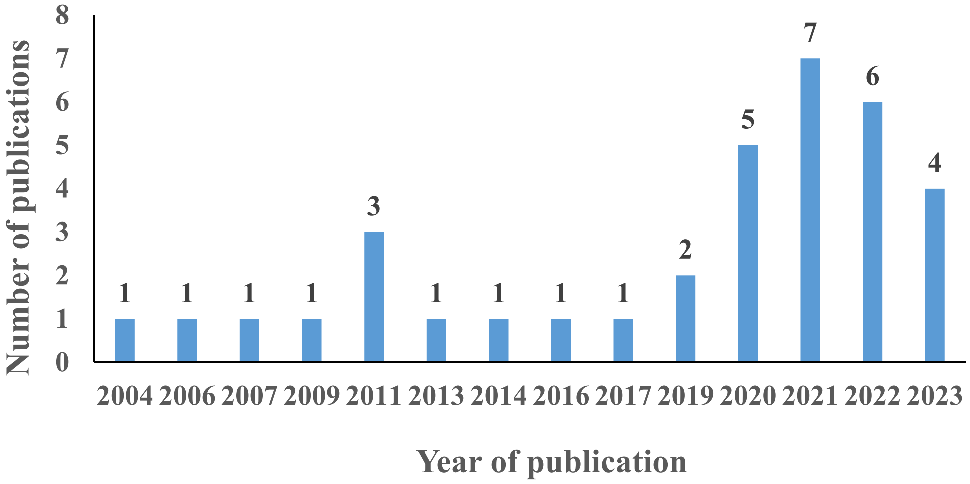


Fig. 3. Relationship between the number of publications and year of publication in studies evaluating the effect of nitrogen fertilization in tropical pastures on forage production, animal performance, and greenhouse gas emissions.

The primary studies included in this systematic review encompass a broad range of climatic conditions, spanning Tropical (A) and Subtropical/Temperate (C) regions according to the Köppen–Geiger classification. Tropical climates predominate in the dataset, representing approximately 73.5% of the studies, and are mainly characterized by the Tropical savanna with a dry season (Aw) type (58.8%; e.g., Jaboticabal, Campo Grande). These regions typically exhibit mean annual maximum temperatures ranging from 28 °C to 32 °C and annual precipitation between 1200 and 1600 mm, with a well-defined dry winter. The remaining tropical climates comprise the Monsoon tropical (Am) and Tropical rainforest (Af) types, each accounting for 5.8% of the studies, with higher annual rainfall (>1800 mm) and mean minimum temperatures between 20 °C and 24 °C, including transitional areas such as Itabela, BA (2.9%). The remaining 26.5% of the studies were conducted in Subtropical/Temperate regions, encompassing Subtropical highland with dry winter (Cwa) (23.5%; e.g., Viçosa, Lavras, Piracicaba) and Humid subtropical (Cfa) (5.9%; Paraná) climates. These regions are characterized by milder mean annual temperatures, with maxima between 24 °C and 28 °C, minima between 12 °C and 17 °C, and annual precipitation ranging from 1400 to 1800 mm.

A wide variation was observed in the duration of the experiments, ranging from 38 to 1.460 days. Among the experimental conditions, 69.7% of the studies were conducted under grazing and 30.3% in plots (Table 2). There was considerable variability in soil types, with 47.1% of the studies carried out in dystric Red Latosol, 5.9% in dark Red Latosol, and 47% in other soil types (Table 2).

Among the grazing studies, 58.3% adopted the continuous grazing method, 37.5% used intermittent and/or rotational grazing, and 4.2%

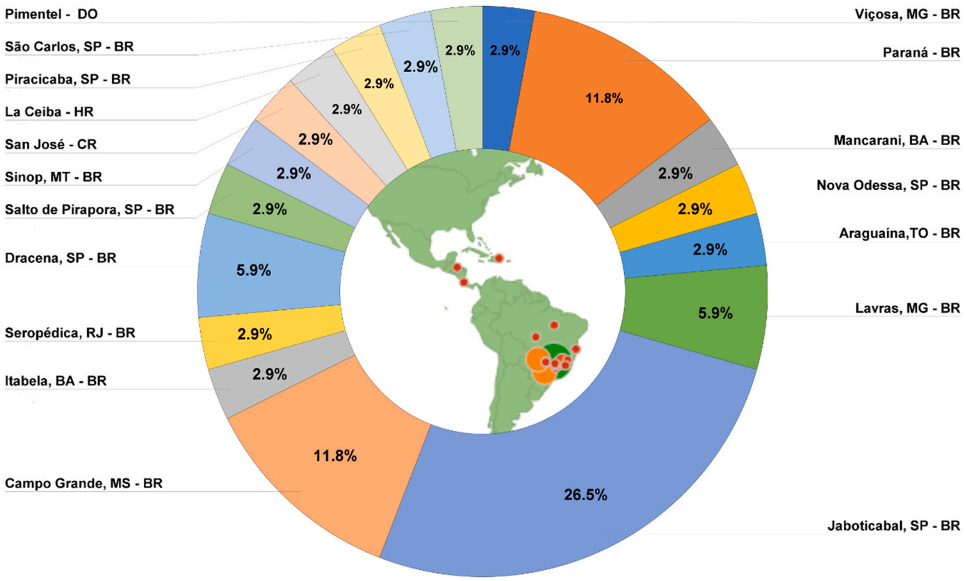


Fig. 4. Location of the studies that made up the sample analyzed in the Systematic Review. **Note:** DO=Dominican Republic, BR=Brazil, HR=Honduras, CR=Costa Rica, SP=São Paulo, RJ=Rio de Janeiro, MS=Mato Grosso do Sul, BA=Bahia, MG=Minas Gerais.

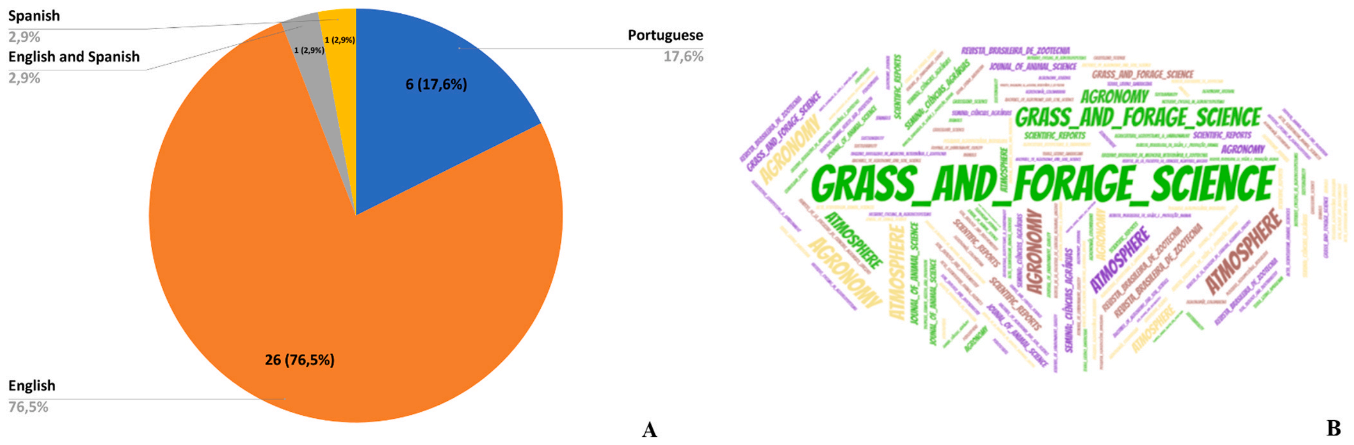


Fig. 5. Frequency of languages in which studies were published (A) and word cloud showing the journals in which the studies were published (B).

did not report the grazing method. Regarding grazing management targets, 68.8% of the studies used pasture height as a management tool, 25% adopted fixed-day management, and 4.0% did not provide this information.

Regarding the tropical forage genera and species studied, 52.9% of the studies were conducted with *Brachiaria brizantha*, 26.5% with *Panicum maximum*, 5.9% with *Brachiaria decumbens*, 5.9% with *Cynodon dactylon*, and 8.7% with other species. The forage cultivars used were Marandu (50.0%), Tanzânia (14.7%), Mombaça (11.8%), other cultivars (11.6%), and in 11.8% of the studies the cultivar was not specified.

The nitrogen (N) sources tested were urea (53.2%), ammonium nitrate (25.5%), ammonium sulfate (8.5%), and other sources (8.5%). Urea was the exclusive N source in 47.1% of the studies, followed by ammonium nitrate in 17.6%. In 64.7% of the studies, N sources were tested in combination, either by evaluating the effect of each individually or in association with N-loss-inhibiting molecules such as nitrapyrin (a nitrification inhibitor) and NBPT (N-(n-butyl) thiophosphoric triamide), a urease inhibitor.

There was variation in the N rates tested, ranging from 0 (control) to 1000 kg/ha of N. In 41.2% of the studies, the N rate was split into three applications, 8.8% into four applications, and 8.8% into two applications. Nitrogen was applied in a single dose in only 8.8% of the studies, and in 32.4%, it was divided into other amounts.

Of the final sample (n = 34), 16 studies included animal evaluations, all involving cattle. The total population was 450 animals, considering only the studies that reported this information in the methods section (n = 7) (Table 3). Regarding the breeds and/or crossbreeds of the experimental animals, 73.7% of the animals were of the Nelore breed and 26.3% were crossbreeds (Table 3). Based on the weights of the animals, the cattle used in the experiments were mostly animals that were in the growing phase (Table 3).

3.3. *Effect of nitrogen fertilization on forage production, chemical composition, and animal performance*

Of the final sample (n = 34), 16 studies included at least one animal performance variable, such as stocking rate (SR), average daily gain (ADG), and gain per area (GPA).

In 15 of these studies, in addition to animal performance metrics, at least one variable related to forage production was also evaluated, such as forage mass (FM) and forage accumulation rate (FAR). In 10 studies, alongside animal performance and forage production variables, information on the chemical composition of the forage was also available, e.g., crude protein (CP), neutral detergent fiber (NDF), and acid detergent

Table 2
Characteristics of the studies included in the systematic review ($n = 34$).

Reference	Soil type	Species and cultivar	Experimental cond.	N source	Language of Publication	Country
Martha et al. (2004)	Eutrudox Kandiudalf	*Pennisetum purpureum**	Plot	UR and AS	English	Brazil
Primavesi et al. (2006)	Typic dystric Red Latosol	*Cynodon dactylon* cv. Coastcross	Plot	UR and AN	Portuguese	Brazil
Euclides et al. (2007)	Dystric Red Latosol	*Panicum maximum* cv. Mombaça	Grazing	UR	Portuguese	Brazil
Canto et al. (2009)	Dystric Red Latosol	*Panicum maximum* cv. Tanzania	Grazing	AN	English	Brazil
Moreira et al. (2011)	Red-Yellow Latosol	*Brachiaria decumbens* cv. Basilisk	Grazing	Not available	Portuguese	Brazil
Ribeiro et al. (2011)	Dark Red Latosol	*Panicum maximum* cv. Tanzania	Grazing	UR	Portuguese	Brazil
Gimenes et al. (2011)	Dystric Red Latosol	*Brachiaria brizantha* cv. Marandu	Grazing	UR and AN	Portuguese	Brazil
Morais et al. (2013)	Argisol	*Pennisetum purpureum Schum**	Plot	UR	English	Brazil
Pinheiro et al. (2014)	Dark Red Latosol	*Panicum maximum* cv. Tanzania	Grazing	UR and AN	Portuguese	Brazil
Aguilar et al. (2016)	Eutrophic Red-Yellow Podzol	*Brachiaria brizantha* cv. Marandu	Grazing	UR	English	Brazil
Cecato et al. (2017)	Red-Yellow Argisol	*Panicum maximum* cv. Tanzania	Grazing	80% UR and 20% AS	English	Brazil
Delevatti et al. (2019)	Latosol	*Brachiaria brizantha* cv. Marandu	Grazing	UR	English	Brazil
Berça et al. (2019)	Not mentioned	*Brachiaria brizantha* cv. Marandu	Grazing	UR	English	Brazil
Longhini et al. (2020)	Dystric Red Latosol	*Brachiaria brizantha* cv. Marandu	Grazing	UR	English	Brazil
Da Silva et al. (2020)	Typic orthic quartz-sandy Neosol	*Panicum maximum* cv. Mombaça	Grazing	AS	English	Brazil
Raposo et al. (2020)	Latosol	*Brachiaria brizantha* cv. Marandu	Grazing	UR	English	Brazil
Do Nascimento et al. (2021)	Dystric ferric Red Latosol	*Brachiaria brizantha* cv. Marandu	Plot	UR and AS	English	Brazil
Gurgel et al. (2020)	Dystric Red Latosol	*Panicum maximum* cv. Mombaça	Grazing	UR	English	Brazil
Homem et al. (2021)	Latosol	*Brachiaria brizantha* cv. Marandu	Grazing	UR	English	Brazil
Ongaratto et al. (2021)	Typic dystric Red Latosol	*Brachiaria brizantha* cv. Marandu	Grazing	AN	English	Brazil
Gurgel et al. (2021)	Dystric Red Latosol	*Panicum maximum* cv. Mombaça	Grazing	UR	English and Spanish	Brazil
Bento et al. (2021)	Clayey Red Latosol	*Brachiaria brizantha* cv. Marandu	Plot	AN	English	Brazil
Corrêa et al. (2021)	Latosol	*Brachiaria brizantha* cv. Marandu	Plot	UR, AN, and AS	English	Brazil
Pérez-Castillo et al. (2021)	Typic Haplustand	*Cynodon nlemfuensis**	Plot	UR and UR + nitrapyrin	English	Costa Rica
Núñez-Ramos et al. (2021)	Not available	*Cynodon dactylon* cv. bermuda	Grazing	UR	Spanish	Dominican Republic
Guimarães et al. (2022)	Dystric Red Latosol	*Brachiaria brizantha* cv. Marandu	Grazing	UR	English	Brazil
Lima et al. (2022a)	Typic dystric Red Latosol	*Brachiaria brizantha* cv. Marandu	Grazing	AN	English	Brazil
Lima et al. (2022b)	Typic dystric Red Latosol	*Brachiaria brizantha* cv. Marandu	Grazing	AN	English	Brazil
Rodrigues et al. (2022)	Latosol	*Brachiaria brizantha* *	Plot	UR	English	Honduras
Euclides et al. (2022)	Dystric Red Latosol	*Panicum maximum* cv. Mombaça	Grazing	UR	English	Brazil
Dos Santos et al. (2023)	Dystrocohesive Yellow Latosol	*Brachiaria brizantha* cv. Marandu	Grazing	UR	English	Brazil
Cassimiro et al. (2023)	Dystric Red-Yellow Argisol	*Brachiaria brizantha* cv. Marandu	Plot	UR, AN, UR + NBPT, UR + duromide	English	Brazil
Meirelles et al. (2023)	Typic Red-Yellow Argisol	*Brachiaria decumbens* *	Plot	UR, AN, UR + NBPT	English	Brazil
Ongaratto et al. (2023)	Typic dystric Red Latosol	*Brachiaria brizantha* cv. Marandu	Grazing	AN	English	Brazil

(*) The cultivar was not presented in the study. UR: urea; AN: ammonium nitrate; AS: ammonium sulfate; Cond: condition. NBPT: N-(n-butyl) thiophosphoric triamide.

fiber (ADF) (Table 4).

Two studies (Da Silva et al., 2020; Delevatti et al., 2019) reported in full the variables related to forage production, chemical composition, and animal performance. The former was conducted on Marandu grass pastures under continuous grazing, while the latter was carried out on Mombaça grass pastures under intermittent grazing.

One study (Euclides et al., 2007) reported only two animal performance variables (SR and ADG), without information on forage production or chemical composition. Among the three forage chemical composition variables, CP was evaluated in ten studies: (Moreira et al.,

Table 3
Characterization of the animal population of the studies included in the systematic review (n = 16).

Reference	Total N exp.$^{(1)}$	N test animals$^{(2)}$	Sex	Category	Initial weight (kg)	Breed or crossbreed
Euclides et al. (2007)	NA	04	M	Steers	NA	Nellore
Canto et al. (2009)	NA	03	M	Bulls	300	Nellore
Gimenes et al. (2011)	48	03	NA	NA	327	Nellore
Ribeiro et al. (2011)	NA	03	M	Steers	210	Nellore
Moreira et al. (2011)	NA	02	M	Steers	Year 1: 180 Year 2: 217	Holstein × Zebu
Pinheiro et al. (2014)	NA	03	M	Steers	230	Nellore
Aguilar et al. (2016)	48	02	F	Heifers	178.69 ± 26.67	Nellore
Cecato et al. (2017)	NA	03	M	Steers	330 ± 3.82	Nellore × Red Angus
Delevatti et al. (2019)	72	06	M	Bulls	Year 1: 352 ± 5 Year 2: 334 ± 2 Year 3: 315 ± 6	Nellore
Da Silva et al. (2020)	50	04	M	Steers	173 ± 1.95	Nellore
Ongaratto et al. (2021)	48	03	M	Bulls	308 ± 20	Nellore
Homem et al. (2021)	NA	02	F	Heifers	234 ± 36	Nellore
Gurgel et al. (2021)	54	NA	M	Steers	205 ± 26	Nellore
Dos Santos et al. (2023)	NA	02	F	Heifers	244 ± 7	Nellore
Euclides et al. (2022)	54	06	M	Steers	285 ± 14	½Senepol × ½Caracu ½Brahman × ½Angus
Lima et al. (2022a)	76	04	M	Bulls	273.7 ± 7.6	Nellore

2011), (Cecato et al., 2017), (Pinheiro et al., 2014), (Delevatti et al., 2019), (Homem et al., 2021), (Lima et al., 2022a), (Da Silva et al., 2020), (Euclides et al., 2022), (Dos Santos et al., 2023), and (Gimenes et al., 2011). Neutral detergent fiber was evaluated in eight studies: (Cecato et al., 2017), (Pinheiro et al., 2014), (Delevatti et al., 2019), (Homem et al., 2021), (Lima et al., 2022a), (Gimenes et al., 2011), (Da Silva et al., 2020), and Dos Santos et al. (2023). Acid detergent fiber was evaluated in four studies: (Delevatti et al., 2019), (Lima et al., 2022a), (Da Silva et al., 2020), and (Gimenes et al., 2011).

The only variable reported in all 16 studies was SR (Table 3), followed by FM, which was presented in 13 studies: (Moreira et al., 2011), (Cecato et al., 2017), (Ribeiro et al., 2011), (Pinheiro et al., 2014), (Canto et al., 2009), (Delevatti et al., 2019), (Ongaratto et al., 2021), (Homem et al., 2021), (Lima et al., 2022a), (Aguilar et al., 2016), (Da Silva et al., 2020), (Dos Santos et al., 2023), and (Gurgel et al., 2021).

The variables with the least available data were FAR and ADF. Regarding FAR, this variable was more frequently reported in studies conducted under rotational and/or intermittent grazing (five studies): (Da Silva et al., 2020), (Gimenes et al., 2011), (Euclides et al., 2022), (Dos Santos et al., 2023), and (Gurgel et al., 2021). Conversely, under continuous grazing, only two studies reported FAR: (Delevatti et al., 2019) and (Ongaratto et al., 2021).

Although the sample included studies with four genera and five species of tropical forages, those reporting animal performance data involved only two genera: *Brachiaria* and *Panicum* (Table 4). Among the studies with animal performance data, 43.75% were conducted with *Brachiaria brizantha* cv. Marandu, 31.25% with *Panicum maximum* cv. Tanzânia, 18.75% with *Panicum maximum* cv. Mombaça, and 6.25% with *Brachiaria decumbens* cv. Basilisk.

The N rates tested varied by forage genus. For *Brachiaria*, rates ranged from 0 to 300 kg/ha, whereas for *Panicum*, rates ranged from 50 to 450 kg/ha.

In 50% of the studies, N fertilization significantly increased FM, as well as SR and GPA (Table 4). In contrast, variables related to forage chemical composition and ADG showed smaller responses to increasing N rates.

By grouping the averages of similar studies with *Brachiaria*, presented in Table 4, it can be observed that increasing N doses from 0 to 270–300 kg ha^{-1} of N increased the SR by 2.6 times (157.7%), the ADG by 1.3 times (31.0%), and the GPA by 2.9 times (189.4%) (Fig. 6). The grouped data for the 0 kg N ha^{-1} treatment in studies with *Brachiaria* were compiled from (Aguilar et al., 2016), (Delevatti et al., 2019), (Ongaratto et al., 2021), Lima et al. (2022), and Dos Santos et al. (2023). Data corresponding to the 270–300 kg N ha^{-1} treatment were obtained from (Moreira et al., 2011) and (Delevatti et al., 2019).

By grouping the averages of similar studies with *Panicum* (Table 5), it can be observed that increasing N doses from 50 to 75–400–450 kg ha^{-1} of N increased the SR by 2.9 times (195.4%) and the GPA by 1.8 times (77.2%), while the ADG showed only a slight increase of 1.02 times (1.6%) (Fig. 6). The grouped data for doses of 50–75 kg N ha^{-1} in studies with *Panicum* were compiled from (Euclides et al., 2007), (Ribeiro et al., 2011), (Pinheiro et al., 2014), and (Cecato et al., 2017). Data for doses of 400–450 kg N ha^{-1} were obtained from (Canto et al., 2009), (Cecato et al., 2017), and Da Silva et al. (2020).

3.4. *Effect of nitrogen on greenhouse gas (GHG) emissions*

3.4.1. *Indirect emissions*

3.4.1.1. NH_3 volatilization. Of the analyzed sample, nine studies reported the effects of nitrogen fertilization on NH_3 volatilization in tropical pastures. However, six of these focused specifically on N loss via NH_3 due to nitrogen fertilization: (Martha et al., 2004), Morais et al. (2013),(Corrêa et al., 2021), (Cassimiro et al., 2023), Pérez-Castillo et al. (2021), and (Meirelles et al., 2023) (Table 5). In three studies (Guimarães et al., 2022; Longhini et al., 2020; Ongaratto et al., 2023), N loss as NH_3 was observed through animal excreta in tropical pastures fertilized with N (Table 6).

Of these studies, 55% were conducted in *Brachiaria brizantha* pastures, 22.22% in *Pennisetum purpureum*, and 11.11% in *Cynodon* and *Brachiaria decumbens*, respectively. All six studies that evaluated only NH_3 losses from nitrogen fertilization (without excreta effects) were conducted in plots, while the three studies involving NH_3 losses through excreta were conducted under grazing conditions.

The most commonly used technique for quantifying NH_3 loss was the semi-open chamber method, with most studies following the methodology described by Araújo et al. (2009). Regarding N sources, UR was the most frequently tested, either alone or in combination with molecules that inhibit N loss.

The N rates evaluated ranged from 0 to 270 kg/ha. Fractionation of N rates was another relevant aspect in these studies. Some studies (Cassimiro et al., 2023; Corrêa et al., 2021; Meirelles et al., 2023) evaluated NH_3 losses based on the division of the full N rate associated with the tested N sources. The minimum N rate applied was 20 kg/ha, and the maximum was 50 kg/ha.

Among the studies assessing NH_3 losses through excreta in N-fertilized pastures, only (Guimarães et al., 2022) reported an increase in NH_3 emissions from excreta in Marandu grass pastures fertilized with

Table 4
Variables related to forage production, chemical composition, and metrics of animal performance in 16 studies involving tropical forages fertilized with N.

Reference		Grazing management target	N rate (kg/ ha N)	Forage production		Chemical composition			Performance metric		
	Species and cultivar			FM (kg/ha DM)	FAR (kg/ha/ day)	CP (%)	NDF (%)	ADF (%)	SR (AU/ha)	ADG (kg/ animal/ day)	GPA (kg/ha/ LW)
Continuous grazing											
Moreira et al. (2011)	*Brachiaria decumbens* cv. Basilisk	20 cm	75	6782.1	-	9.90	-	-	3.60	0.485	404.2
			150	7336.7	-	11.40	-	-	4.19	-	515.4
			225	7891.4	-	13.00	-	-	4.70	-	626.6
			300	8446.0	-	14.50	-	-	5.30	0.610	737.8
Cecato et al. (2017)	*Panicum maximum* cv. Tanzania	50 cm	50	14.178	-	6.85	76.44	-	4.00	0.990	653.0
			100	11.995	-	7.29	75.63	-	3.70	1.150	675.0
			200	14.263	-	7.57	76.00	-	5.00	1.030	723.0
			400	13.685	-	8.58	74.23	-	6.60	1.100	813.0
Ribeiro et al. (2011)*	*Panicum maximum* cv. Tanzania	40–45 cm	75	2291.0	-	-	-		1.89	0.670	-
			150	2291.0	-	-	-		2.42	0.710	-
			225	2803.0	-	-	-		2.55	0.730	-
Pinheiro et al. (2014)*	*Panicum maximum* cv. Tanzania	40–45 cm	75	4764.0	-	12.69	74.00	-	2.33	0.860	456.76
			150	5244.0	-	13.39	72.75	-	2.62	0.780	473.48
			225	6702.0	-	13.95	71.75	-	3.10	0.840	607.24
Canto et al. (2009)	*Panicum maximum* cv. Tanzania	60 cm	100	6600.0	-	-	-	-	3.23	0.770	436.73
			200	8100.0	-	-	-	-	4.52	0.700	595.73
			300	8237.0	-	-	-	-	5.81	0.730	754.73
			400	9670.0	-	-	-	-	7.10	0.710	913.73
Delevatti et al. (2019)	*Brachiaria brizantha* cv. Marandu	25 cm	0	5798.0	31.36	11.36	60.62	29.81	3.37	0.939	514.00
			90	6345.0	51.26	13.55	58.60	28.73	4.64	0.985	769.00
			180	6436.0	71.16	15.09	56.40	27.87	5.81	0.879	848.00
			270	6499.0	91.06	16.76	55.90	27.62	6.55	0.898	967.00
Ongaratto et al. (2021)*	*Brachiaria brizantha* cv. Marandu	25 cm	0	5150.0	76.10	-	-	-	1.90	-	-
			75	5500.0	117.10	-	-	-	2.80	-	-
			150	5550.0	104.80	-	-	-	3.80	-	-
Homem et al. (2021)	*Brachiaria brizantha* cv. Marandu	20–25 cm	0	3397.7	-	9.10	61.09	-	2.30*	0.544*	106*
			150	5523.5	-	13.08	58.00	-	3.80*	0.636*	219*
Lima et al., 2022a)	*Brachiaria brizantha* cv. Marandu	25 cm	0	4600.0	-	11.0	47.80	21.50	1.78	0.710	111
			75	5300.0	-	14.7	48.90	19.90	3.07	0.850	213
			150	5000.0	-	17.3	47.50	21.60	3.68	0.930	289
Aguilar et al. (2016)	*Brachiaria brizantha* cv. Marandu	Not available	0	3224.5	-	-	-	-	1.55	0.245	-
			50	3787.0	-	-	-	-	2.85	0.446	-
			100	3860.5	-	-	-	-	3.00	0.410	-
			150	4281.0	-	-	-	-	3.00	0.449	-
Intermittent/Rotational grazing											
Da Silva et al. (2020)	*Panicum maximum* cv. Mombaça	Fixed days	150	6767.5	188.4	12.89	71.00	35.87	5.47	0.420	587.21
			300	7204.7	211.7	19.25	68.70	35.69	6.36	0.510	799.24
			450	8068.2	254.7	20.41	67.51	33.20	7.48	0.485	909.61
Gimenes et al. (2011)	*Brachiaria brizantha* cv. Marandu	25 and 35 cm	50	-	29.1	-	64.47	33.41	2.55	-	630.00
			200	-	51.9	-	61.72	32.99	3.44	-	720.00
Euclides et al. (2022)	*Panicum maximum* cv. Mombaça	80–90 cm	100	-	41.1	10.80	-	-	3.0	-	-
			200	-	55.1	11.50	-	-	3.7	-	-
			300	-	69.1	12.20	-	-	4.4	-	-
Dos Santos et al. (2023)	*Brachiaria brizantha* cv. Marandu	Fixed days	0	1483.0	12.5	8.77	66.90	-	2.23	0.404	-
			150	2082.0	22.2	9.79	65.70	-	3.21	0.461	-
Gurgel et al., 2021)	*Panicum maximum* cv. Mombaça	Fixed days	100	3371.8	26.7	-	-	-	2.70	-	466.70
			200	3637.6	36.3	-	-	-	3.10	-	535.90
			300	3853.9	43.4	-	-	-	4.00	-	691.50
Euclides et al. (2007)	*Panicum maximum* cv. Mombaça	Fixed days	50	-	-	-	-	-	2.00	0.430	-
			100	-	-	-	-	-	2.30	0.455	-

Note: FM: forage mass; FAR: daily forage accumulation rate; DM: dry matter; AU: animal unit; CP: crude protein; NDF: neutral detergent fiber; ADF: acid detergent fiber; Numbers in parentheses correspond to the caption of the studies in the text; (*) in the study by Homem et al. (Homem et al., 2021), one animal unit was considered 500 kg of live weight; (*) in the studies by Ribeiro et al. (Ribeiro et al., 2011) and Pinheiro et al. (Pinheiro et al., 2014), the FM means were calculated considering the entire experimental period; (*) in the study by Ongaratto et al. (Ongaratto et al., 2021), the 'SR' variable in each treatment was reported in the study methods.

150 kg/ha of N. In the study by Ongaratto et al. (2023), ammonium nitrate (AN) was used as the N source, and NH_3 emissions from excreta were lower at the 150 kg/ha N rate compared to the control.

In the studies by (Martha et al., 2004), Pérez-Castillo et al. (2021), (Corrêa et al., 2021), (Cassimiro et al., 2023), and (Meirelles et al., 2023) (Table 5), the N source associated with the highest NH_3 losses was UR, even when the total N rate was applied fractionally. In three of these studies (Pérez-Castillo et al., 2021; Cassimiro et al., 2023; Meirelles et al., 2023), UR was tested in combination with N loss inhibitors. Two studies reported reduced NH_3 losses with these combinations, notably the UR + NBPT treatment in the study by Meirelles et al. (2023) and the UR + duromide treatment in the study by Cassimiro et al. (2023).

Data from the study by Corrêa et al. (2021) shows that when the 90 kg/ha dose of N is split into three applications of 30 kg/ha of N, there is a 54.63% reduction in N loss through NH_3. The dose of 180 kg/ha of N, when split into three applications of 60 kg/ha of N, reduces losses by 55.45%. And fractioning the dose of 270 kg/ha of N into three applications of 90 kg/ha of N can reduce N loss by NH_3 by 45.96% when the source is UR, according to Table 5.

Based on the data from the studies by Cassimiro et al. (2023) and

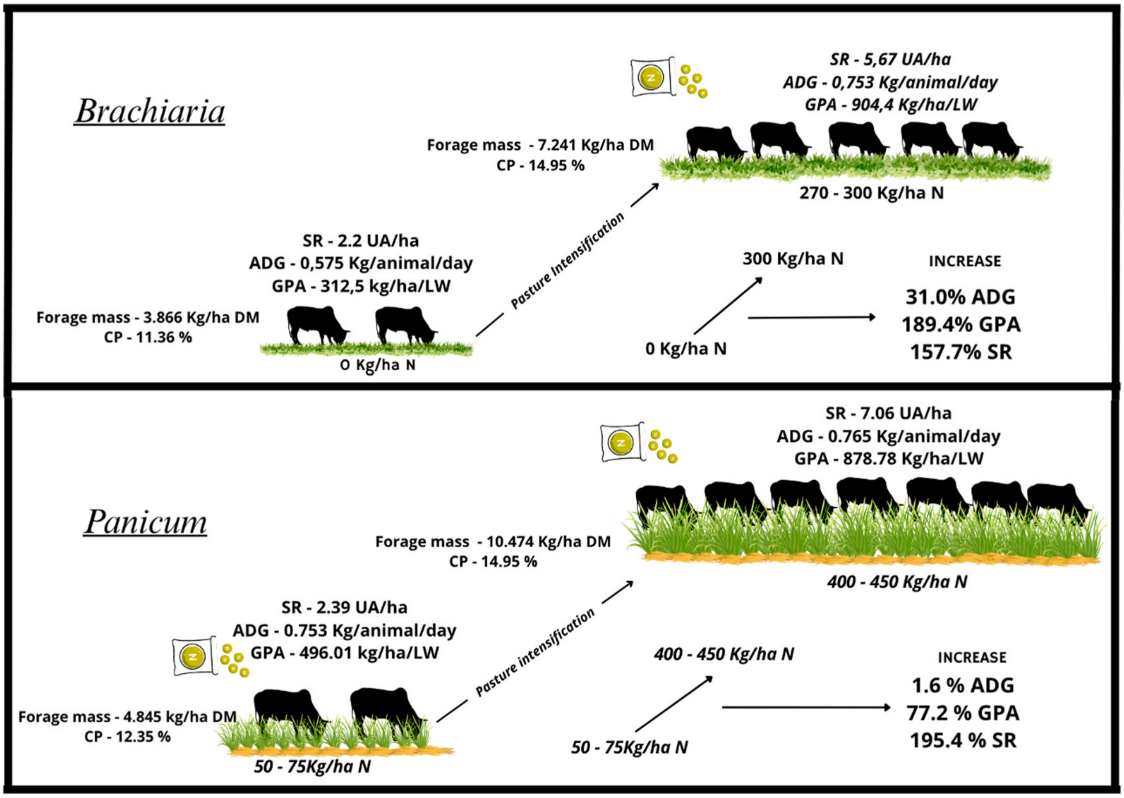


Fig. 6. Potential increase in animal production with the use of N in forage plants of the *Brachiaria* and *Panicum* genera.

Meirelles et al. (2023), when the N source was AN, the increase in N doses from 100 to 200 kg/ha of N increased N losses by NH_3 by 14.68% and 18.48%, respectively in each study, according to Table 5.

3.5. Direct emissions

3.5.1. N_2O emissions

N_2O emissions were evaluated in eight studies, five of which were conducted in plots and three under grazing conditions (Table 7). Among these, 62.5% were carried out with forages of the *Brachiaria* genus, 25% with *Cynodon*, and 12.5% with *Pennisetum*.

The main technique for measuring N_2O emissions was the use of closed static chambers, with most studies following the methodology described by Mosier and Heinemeyer (1985). Urea was the most commonly studied N source, evaluated in six of the eight studies. Nitrogen application rates ranged from 0 to 270 kg/ha.

Two studies (Morais et al., 2013; Bento et al., 2021) evaluated not only the effect of nitrogen fertilization but also the influence of soil tillage for pasture establishment. In both studies, N was applied in a single dose (without fractionation). The results indicate that increasing N rates lead to greater N_2O emissions (Table 7).

The data from the study by Raposo et al. (2020) shows that when the N source used was UR, the increase in N doses from 90 to 270 kg/ha of N can increase N_2O emissions by 80.46%, based on Table 7. In the study by Do Nascimento et al. (2021), when the N source was UR, increasing the N doses from 40 to 80 kg/ha of N increased N_2O emissions by 55.09%, while when the source was AS, the increase was 33.32%, based on Table 7.

3.6. CO_2 and CH_4 emissions

CO_2 emissions were assessed in two studies (Bento et al., 2021; Raposo et al., 2020) while CH_4 emissions from soil were analyzed only in the study by Raposo et al. (2020) (Table 8). It should be noted, however, that Raposo et al. (2020) evaluated both gases. Both studies were conducted in *Brachiaria brizantha* cv. Marandu pastures.

In the study by Bento et al. (2021), gas sampling was performed using cylindrical chambers, following the methodology described by Davidson et al. (2002). And in Raposo et al. (2020), gases were evaluated using two techniques, for soil CH_4, they were evaluated using the static chamber method (Mosier and Heinemeyer, 1985). Soil CO_2 emissions were measured by an infrared spectrometer according to Healy et al. (1996) using a portable system (LI-8100, LI-COR Biosciences).

The N sources used were AN (Bento et al., 2021) and UR (Raposo et al., 2020), with N rates ranging from 0 to 270 kg/ha. Fractionation of N rates was performed only in the study by Raposo et al. (2020). As noted in the section on N_2O emissions, Bento et al. (2021) also investigated the combined effects of nitrogen fertilization and soil tillage on CO_2 emissions in tropical pastures.

In the study by Raposo et al. (2020), CO_2 emissions increased between the control and the other N rates, showing a cubic response. On the other hand, CH_4 emissions decreased as N rates increased. In the study by Bento et al. (2021), cumulative CO_2 emissions were similar between the 0 and 60 kg/ha N treatments (Table 8).

3.7. Enteric CH_4 emissions

Enteric CH_4 emissions were evaluated in two studies (Berça et al., 2019; Lima et al., 2022a) (Table 9), conducted in *Brachiaria brizantha* cv. Marandu pastures. The N rates ranged from 0 to 150 kg/ha; however, the N source used by Berça et al. (2019) was UR, whereas AN was used in the study by Lima et al. (2022a).

The animal categories differed between the studies. Berça et al. (2019) used heifers to estimate enteric CH_4 emissions, while Lima et al. (2022a) evaluated bulls. In both studies, the tracer gas SF_6 technique was used to assess gas emissions.

The variables commonly evaluated included CH_4 g/animal/day, CH_4

g/kg of DM, and CH_4 conversion rate (Ym %). None of these variables were significantly affected by the N rates and/or sources used in the respective studies (Table 9).

Table 5

NH_3 volatilization in N-fertilized tropical pastures.

Reference	N source	N rate (kg/ha)	N fractionation (kg/ha)	NH_3 volatilization
Martha et al. (2004)*	UR	100	SD	45.2 kg/ha NH_3
	UR	136	SD	44.6 kg/ha NH_3
	AS	100	SD	12 kg/ha NH_3
Morais et al. (2013)	UR	80	SD	47 kg/ha NH_3
		100	SD	42 kg/ha NH_3
		80	SD	36 kg/ha NH_3
Corrêa et al. (2021)	UR	90	SD and 30	13.9% (UF); 6.3% (F)
		180	SD and 60	24.4% (UF); 10.9% (F)
		270	SD and 90	44.6% (UF); 24.1% (F)
	AN	90	SD and 30	2.02% (UF); 1.05% (F)
		180	SD and 60	3.17% (UF); 2.58% (F)
		270	SD and 90	7.71% (UF); 5.67% (F)
	AS	90	SD and 30	2.22% (UF); 0.78% (F)
		180	SD and 60	3.1% (UF); 1.88% (F)
		270	SD and 90	5.27% (UF); 3.65% (F)
Cassimiro et al. (2023)	UR	100	25	5.49 kg/ha NH_3
	UR	200	50	10.66 kg/ha NH_3
	UR + NBPT	100	25	2.48 kg/ha NH_3
	UR + NBPT	200	50	3.76 kg/ha NH_3
	UR + duromide	100	25	1.93 kg/ha NH_3
	UR+ duromide	200	50	2.59 kg/ha NH_3
	AN	100	25	1.22 kg/ha NH_3
	AN	200	50	1.43 kg/ha NH_3
Pérez-Castillo et al. (2021)	C	0	-	6.28 kg/ha NH_3
	UR	250	41.7	12.30 kg/ha NH_3
	UR + nitrapyrin	250	41.7	13.51 kg/ha NH_3
Meirelles et al. (2023)	UR + NBPT	100	20	12.40 kg/ha NH_3
	UR + NBPT	200	40	17.80 kg/ha NH_3
	AN	100	20	7.50 kg/ha NH_3
	AN	200	40	9.20 kg/ha NH_3
	UR	100	20	17.40 kg/ha NH_3
	UR	200	40	33.70 kg/ha NH_3

Note: (*) In the study by Martha et al., (Martha et al., 2004), the data reported in the table refer to experiment 2, considering the average cumulative losses during the summer season; UR: urea; AN: ammonium nitrate; AS: ammonium sulfate; C: control; SD: single dose; UF: unfractionated; F: fractionated rate; NBPT: N-(n-butyl) thiophosphoric triamide.

Table 6

NH_3 volatilization (% of N emitted as NH_3) from cattle excreta in N-fertilized tropical pastures.

Reference	N source (kg/ha N)	N fractionation (kg/ha N)	Excreta	N rate (kg/ha)	
Longhini et al. (2020) *	UR	50		0	150
			Feces	1.60	2.60
			Urine	10.70	13.80
Guimarães et al. (2022)	UR	50		0	150
			Feces	0.52	4.70
			Urine	1.02	12.61
Ongaratto et al. (2023)	AN	50		0	150
			Feces	6.75	2.28
			Urine	14.1	3.27

Note: UR: urea; AN: ammonium nitrate; (*); In the study by Longhini et al. (Longhini et al., 2020), the data reported in the table were available in the article's supplementary material.

Table 7

N_2O emissions from N-fertilized tropical pastures.

Reference	N source	N rate (kg/ha)	N fractionation (kg/ha)	N_2O emission
Morais et al. (2013)	UR	80	SD	436 g/ha N
		100	SD	572 g/ha N
		80	SD	1.468 g/ha N
Bento et al. (2021)	C	0	-	0.20 mg m-2 day-1
	AN	60	SD	1.13 mg m-2 day-1
Do Nascimento et al. (2021)	C	0	-	8.39 µg N-N_2O m^{-2} hr^{-1}
	UR	40	SD	16.40 µg N-N_2O m^{-2} hr^{-1}
	UR	80	SD	36.52 µg N-N_2O m^{-2} hr^{-1}
	AS	40	SD	14.45 µg N-N_2O m^{-2} hr^{-1}
	AS	80	SD	21.67 µg N-N_2O m^{-2} hr^{-1}
Guimarães et al. (2022)*	C	0	-	14.3 µg N-N_2O m^{-2} hr^{-1}
	UR	150	50	51.9 µg N-N_2O m^{-2} hr^{-1}
Raposo et al. (2020)	UR	0	-	−5.99 µg N-N_2O m^{-2} hr^{-1}
		90	30	36.14 µg N-N_2O m^{-2} hr^{-1}
		180	60	49.53 µg N-N_2O m^{-2} hr^{-1}
		270	90	185.69 µg N-N_2O m^{-2} hr^{-1}
Núñez-Ramos et al. (2021)	C	0	-	5.60 kg/ha N
	UR	218	SD	11.80 kg/ha N
Rodrigues et al. (2022)	C	0	-	0.27 mg N_2O m^{-2} h^{-1}
	UR	59.47	SD	0.37 mg N_2O m^{-2} h^{-1}
Pérez-Castillo et al. (2021)	C	0	-	1.12 kg/ha N
	UR	250	41.7	2.51 kg/ha N
	UR + nitrapyrin	250	41.7	3.51 kg/ha N

Note: UR: urea; C: control; AN: ammonium nitrate; AS: ammonium sulfate; SD: single dose; (*); In the study by Guimarães et al. (2022), the data reported in the table were available in the article's supplementary material.

3.8. N and C contents

The N content of the soil profile was assessed in two studies (Gurgel et al., 2020; Primavesi et al., 2006). In the study by Primavesi et al. (2006), N rates ranged from 0 to 1000 kg/ha in *Cynodon dactylon* cv. Coastcross, conducted in plots. Nitrogen losses were evaluated based on

Table 8

CO_2 and CH_4 emissions in N-fertilized tropical pastures.

Reference	N source	N rate (kg/ha)	N fractionation (kg/ha)	CO_2 emissions
Raposo et al. (Raposo et al., 2020)	C	0	-	7.19 μmol CO_2 m^{-2} s^{-1}
	UR	90	30	8.36 μmol CO_2 m^{-2} s^{-1}
		180	60	7.77 μmol CO_2 m^{-2} s^{-1}
		270	90	8.05 μmol CO_2 m^{-2} s^{-1}
Bento et al. (Bento et al., 2021)*	C	0	-	15.70 Mg CO_2/ha/year
	AN	60	DU	19.63 Mg CO_2/ha/year
Raposo et al. (Raposo et al., 2020)				CH_4
	C	0	-	61.61 μg CH_4^-C/ m^{-2} h^{-1}
	UR	90	30	24.66 μg CH_4^-C/ m^{-2} h^{-1}
		180	60	22.10 μg CH_4^-C/ m^{-2} h^{-1}
		270	90	24.39 μg CH_4^-C/ m^{-2} h^{-1}

Note: (*) in the study by Bento et al. (Bento et al., 2021) the data reported in the table refer to the average cumulative CO_2 emissions of the second evaluation period of the study; UR: urea; C: control; AN: ammonium nitrate; SD: single dose.

Table 9

Enteric CH_4 emissions from cattle raised on N-fertilized tropical pastures.

Reference	N source	N rate (kg/ha)	N fractionation (kg/ha)	CH_4 emissions		
				CH_4 g/animal/day	CH_4 g/kg DM	Ym (%)
Berça et al. (2019)	C	0	-	115	16.4	4.99
	UR	150	50	140	16.2	4.94
Lima et al. (2022a)	C	0	-	141.2	19.1	6.2
	AN	75	25	173.3	21.7	6.9
	AN	150	50	179.6	22.5	7.1

Note: DM: dry matter; Ym (%): methane conversion rate (energy loss from methane relative to gross energy intake); UR: urea; C: control; AN: ammonium nitrate.

both the N source (UR and AN) and the applied rates, which were split into five applications. In both studies, soil analyses were used to monitor N content.

Gurgel et al. (2020) investigated the residual effect of three N rates (100, 200, and 300 kg/ha) in *Panicum maximum* cv. Mombaça pastures on soil C and N contents. Total C content was similar across treatments, with values of 130.8, 135.5, and 136.7 mg/ha, respectively. In contrast, average N content increased with higher N rates (Table 10).

In the study by Primavesi et al. (2006), N leaching throughout the soil profile was also evaluated. The results showed that pastures fertilized with UR had lower N concentrations at greater depths when compared to those treated with AN, suggesting greater N loss through leaching (Table 10).

3.9. *Emission intensity*

The intensity of GHG emissions associated with nitrogen fertilization in tropical pastures was evaluated in the study by Lima et al. (2022b). Emission intensity refers to the amount of GHG emissions relative to a unit of area or production (e.g., meat, milk).

In this study, a life cycle inventory was developed to estimate GHG emissions resulting from animal activity, including enteric CH_4, N_2O from soil and urine, and CH_4 from manure.

Table 10

N contents in the soil profile of *N-fertilized* tropical pastures.

Reference	N source	N rate (kg/ha)	N fractionation (kg/ha)	Depth (cm)	N content
Primavesi et al. (Primavesi et al., 2006)*	C	0	-	0–40	9.3 kg/ha N-NO_3^-
		0	-	40–80	3.3 kg/ha N-NO_3^-
		0	-	80–200	12.5 kg/ha N-NO_3^-
	UR	250	50	0–40	11.6 kg/ha N-NO_3^-
		250	50	40–80	6.4 kg/ha N-NO_3^-
		250	50	80–200	12.4 kg/ha N-NO_3^-
		1000	200	0–40	28.1 kg/ha N-NO_3^-
		1000	200	40–80	9.4 kg/ha N-NO_3^-
		1000	200	80–200	9.0 kg/ha N-NO_3^-
	AN	250	50	0–40	2.8 kg/ha N-NO_3^-
		250	50	40–80	2.3 kg/ha N-NO_3^-
		250	50	80–200	7.9 kg/ha N-NO_3^-
		1000	200	0–40	96.2 kg/ha N-NO_3^-
		1000	200	40–80	68.2 kg/ha N-NO_3^-
		1000	200	80–200	60.5 kg/ha N-NO_3^-
Gurgel et al. (Gurgel et al., 2020)	UR	100			1.5 mg/ha
		200	**	***	1.6 mg/ha
		300			1.7 mg/ha

Note (*): in the study by Primavesi et al. (Primavesi et al., 2006), the data reported in the table refer to experiment 1; (**) residual effect of N rates; (***) Average of the stock up to 100 cm; C: control; UR: urea; AN: ammonium nitrate.

The inventory was based on data from the study by Lima et al. (2022a); both studies were conducted in the same experimental area and shared the same dataset but addressed it from different approaches.

Lima et al. (2022b) assessed GHG emission intensity (kg CO_2/kg carcass eq^{-1}) across three systems with varying levels of N fertilization in Marandu grass pastures (0, 75, and 150 kg/ha, using AN as the N source). The results indicated similar emission intensities between the control (0 N) and the 75 kg/ha N treatment. However, the 150 kg/ha treatment showed the highest emission intensity when compared to the control. The reported emission intensities were 5.87, 7.32, and 8.35 kg CO_2/kg carcass eq^{-1}, respectively.

4. Discussion

When considering the growing number of studies published in the past five years, nitrogen (N) fertilization remains a central topic in research on tropical forages, with a strong geographic concentration of studies from Brazil and, to a lesser extent, other South and Central American countries. This concentration reflects both the regional predominance of pasture-based livestock systems and the scientific leadership of Brazilian research institutions in this field (Bastidas et al., 2024; Cardoso et al., 2019; Sarabia-Salgado et al., 2023). However, such geographic and linguistic dominance may introduce bias into the global evidence base, particularly regarding the representativeness of results under contrasting tropical edaphoclimatic conditions and farm management realities. Expanding studies beyond these dominant regions is therefore essential to strengthen the external validity of current findings.

Despite the wide variation in experimental durations, 64.28% of the studies that included animal performance measurements were conducted over periods longer than 24 months. Research on nitrogen fertilization commonly spans 24 months or more in order to assess the effects across at least two rainy seasons (Almeida et al., 2023; Almeida et al., 2024).

Among the studies included in this review, 58.3% adopted the continuous grazing method. This is similar to the findings of Costa et al. (2022), who reported that 53.5% of grazing experiments were conducted under continuous grazing. This method is characterized by unrestricted and uninterrupted animal access to the pasture, without rotation or rest periods (Allen et al., 2011). The most commonly used grazing management tool was pasture height, particularly in continuous grazing systems. According to HODGSON (HODGSON, 1990), canopy height (CH) is a variable closely associated with forage production and light interception (LI).

The studies included in this systematic review revealed considerable heterogeneity in experimental conditions, involving diverse soil types, forage species, grazing systems, nitrogen sources, application rates, and durations. This variability complicates the direct comparison of results and underscores the need for more standardized experimental protocols. These methodological asymmetries, combined with the diversity of site conditions, highlight significant data gaps that must be addressed through coordinated, long-term, and multi-environment trials.

Forages of the *Brachiaria* genus were the most studied across all experimental conditions, particularly in Brazil. This can be attributed to the extensive use of these forages in the country; more than 99 million hectares of pastures are composed of *Brachiaria* spp., with the Marandu cultivar accounting for 85% of this total (Poppi et al., 2018).

The range of N rates tested in *Brachiaria* forages was lower compared to those tested in *Panicum* forages. In *Brachiaria*, the rates ranged from 0 to 300 kg/ha of N, whereas in *Panicum*, the range was from 50 to 450 kg/ha of N. The lower rates used in *Brachiaria* studies may be explained by the fact that forages such as Marandu and Basilisk grasses are often used in extensive or low-input systems (Aguilar et al., 2016; Moreira et al., 2011), due to their adaptability to medium- to low-fertility soils and ease of management compared to other genera (Jank et al., 2014).

The absence of 0 kg/ha as a treatment in studies with *Panicum* forages may reflect the higher soil fertility requirements of this genus (Bublitz et al., 2024). According to Domiciano et al. (2021), N rates between 0 and 50 kg/ha are insufficient to optimize the productive response of *Panicum maximum*. Recommendations for nitrogen fertilization in this species generally range from 100 to 150 kg/ha/year (Galindo et al., 2017; Oliveira et al., 2020).

Patterns of forage response to N fertilization confirm that *Panicum* cultivars exhibit higher responsiveness and improved nutritional quality—with higher crude protein and lower neutral detergent fiber (NDF)—which favor digestibility and animal performance under intensified systems (Almeida et al., 2024; Oliveira et al., 2020). These quality improvements are critical intermediaries linking fertilization to animal productivity and greenhouse gas (GHG) emissions. Enhanced digestibility promotes higher dry matter intake (DMI) and more efficient energy use, thus potentially decreasing CH_4 emission intensity (Meo-Filho et al., 2022; Sakamoto et al., 2020). Conversely, excessive N supply without proper nutrient balance, especially phosphorus (P) and potassium (K), can accelerate degradation processes, reducing long-term productivity and ecosystem resilience (Fonte et al., 2014; Primavesi et al., 2006).

Data from most studies on animal performance, particularly those conducted under continuous stocking, indicate that increasing forage mass through higher N rates enhances the carrying capacity of pastures, resulting in higher stocking rates (Canto et al., 2009; Cecato et al., 2017; Delevatti et al., 2019; Lima et al., 2022a; Moreira et al., 2011; Pinheiro et al., 2014). This increase in animal numbers per area improves gain per unit area without significantly affecting the animals' ADG (Sales et al., 2020). However, beyond a certain stocking rate threshold, a trade-off emerges between stocking rate (SR) and ADG, making it impossible to maximize both variables simultaneously. As SR continues to rise, forage allowance per animal declines, reducing the opportunity for selective grazing and ultimately leading to a decrease in ADG (Mott, 1960).

The results regarding N losses through NH_3 volatilization and N_2O emissions highlight strong dependency on fertilizer source, rate, and application timing. Urea, the most commonly used fertilizer due to its low cost, incurred the highest NH_3 losses, whereas ammonium sulfate presented lower losses at higher cost (Do Nascimento et al., 2021). Fractional N application successfully mitigated emissions—particularly when total N was divided into doses of 20–60 kg ha^{-1} —by aligning nutrient availability with plant uptake and microbial demand (Cassimiro et al., 2023; Meirelles et al., 2023). Such strategies improve N use efficiency and align pasture intensification with climate mitigation goals, consistent with the sustainable intensification framework central to tropical livestock systems (Bastidas et al., 2024; Corrêa et al., 2021).

The data from the studies that evaluated N losses through NH_3 and N_2O emissions suggest that the source of N to be used should be aligned with the level of intensification of the production system. In less intensive systems, the use of RH can be recommended due to its lower cost. Therefore, in order to maximize its use, fractioning the annual dose is one of the main strategies to reduce N losses (Chagas et al., 2017; Corrêa et al., 2021; Luo et al., 2010). However, in more intensive production systems, the use of less volatile sources, also associated with fractionation management, helps to increase the efficiency of fertilizer use, leading to lower losses and potentially less environmental impact (Do Nascimento et al., 2021). Such management practices improve fertilizer use efficiency and represent practical mitigation strategies for N-induced emissions in tropical regions.

Although only the study by Raposo et al. (2020) directly evaluated CH_4 emissions from soil in tropical pastures fertilized with nitrogen, their results indicated that N application can stimulate CH_4 consumption by soil microorganisms. However, CH_4 emission patterns in N-fertilized pastures are highly variable (Yue et al., 2016), largely due to the strong influence of climatic factors such as precipitation and temperature (Cardoso et al., 2020). These factors affect CH_4 fluxes through both direct and indirect mechanisms: directly by modifying microbial activity and gas diffusion within the soil matrix; indirectly by altering soil moisture, aeration, and redox potential, which regulate methanogenesis and CH_4 oxidation. For example, high precipitation increases soil water content, promoting anaerobic microenvironments that favor methanogenic archaea activity and therefore CH_4 production. Conversely, well-aerated soils stimulate methanotrophic microorganisms that oxidize CH_4, enabling the soil to function as a net atmospheric CH_4 sink. Thus, the balance between CH_4 production and oxidation in N-fertilized soils depends sensitively on the interplay between climatic conditions and soil physicochemical properties (Wagner, 2017).

Regarding CO_2 emissions, Bento et al. (2021) demonstrated that both nitrogen fertilization and soil cultivation practices significantly influence emissions. Soil disturbance during land preparation disrupts aggregates, exposing previously protected organic matter to enhanced microbial decomposition, which releases organic carbon to the atmosphere and degrades soil quality (Carmo et al., 2007). Within pasture systems, maintaining sustainable management is therefore critical to increase soil carbon stocks (Tenelli et al., 2025) and to improve soil physical structure (Da Costa et al., 2025). These desirable conditions are linked not only to judicious use of nitrogen fertilizers but, importantly, also to the adoption of effective pasture and grazing management practices that preserve soil integrity and promote ecosystem resilience (Brito et al., 2015).

Increased soil CO_2 emissions associated with nitrogen fertilization, as reported by Raposo et al. (2020), are primarily linked to enhanced root and microbial respiration following N input. Fertilization provides readily available nitrogen, stimulating root metabolic activity and accelerating microbial decomposition of soil organic matter, which leads to short-term CO_2 emission peaks, especially in the rainy season when moisture and temperature conditions favor biological activity (Luo et al., 2016). Although excessive soil moisture can create temporary anaerobic microsites inhibiting oxidative processes, the increased microbial and root activity in aerobic zones generally dominates, resulting in net CO_2 emission increases. Over time, as nitrogen is progressively assimilated and labile carbon substrates diminish, respiration rates decline, leading to reduced CO_2 fluxes (Kuzyakov and Gavrichkova, 2010).

While Gurgel et al. (2020) did not observe significant increases in soil carbon stocks, they reported substantial residual effects from applied N rates, largely attributed not only to fertilization management but also to associated factors such as appropriate stocking rate adjustment, controlled grazing intensity, adequate replacement of nutrients, and preservation of residual leaf area after grazing. Segnini et al. (2019) further highlight that intensified tropical pastures tend to have higher carbon stocks in the 0–30 cm soil layer, with well-managed systems potentially acting as long-term carbon sinks.

When nitrogen availability exceeds plant assimilation capacity, nutrient losses become more likely (Xu et al., 2012), explaining observations of higher nitrogen concentrations at soil depth (Primavesi et al., 2006). However, soil microorganisms—including heterotrophic bacteria, fungi, and nitrifiers—temporarily assimilate residual nitrogen into microbial biomass, reducing losses through leaching or volatilization. The subsequent decomposition of this biomass mineralizes nitrogen back into plant-available forms, acting as a natural “buffer” in the soil nutrient cycle. Consequently, aligning fertilization with plant requirements is crucial to minimize nitrogen losses and reduce operational costs (Gu et al., 2023).

The lower emission intensities observed by Lima et al. (2022b) for 0 and 75 kg N/ha treatments in *Brachiaria* forages suggest a threshold beyond which environmental impacts increase despite higher stocking rates. Bastidas et al. (2024) emphasize that applying moderate nitrogen rates can optimize nitrogen use efficiency, improve plant nutrient utilization, and potentially reduce ammonia and nitrous oxide emissions.

Although individual enteric methane emissions from cattle grazing on N-fertilized pastures did not statistically differ among treatments (Table 9), Lima et al. (2022a) reported a stocking rate in the 150 kg N/ha treatment twice that of the control (3.68 vs. 1.78 AU/ha), enabling greater meat production per unit area, which may contribute to reducing production cycles.

Enteric methane emissions are strongly linked to dry matter intake (DMI) and animal body weight, with diet composition further modulating this relationship (Beauchemin et al., 2008; Sakamoto et al., 2020). Both Berça et al. (2019) and Lima et al. (2022a) found similar DMI across N treatments, with values ranging from 7.8 to 8.8 kg/day. Buddle et al. (2011) identify DMI as the most influential factor in ruminant methane emissions; accordingly, CH_4 emissions per unit of ingested dry matter can rise or fall with changes in intake (Reynolds et al., 2010).

Dietary fiber quality, especially neutral detergent fiber (NDF) content, is critical in modulating ruminal fermentation efficiency and CH_4 emissions. High NDF diets promote acetate and hydrogen production, substrates for methanogenesis, increasing energy lost as methane per unit of dry matter intake (Soltan et al., 2013). Conversely, lowering NDF or enhancing fiber digestibility favors propionate production, which competes with methanogenesis, reducing methane yield (Fouts et al., 2022). Nitrogen fertilization often improves forage nutritive quality by boosting crude protein and lowering NDF, which enhances digestibility and animal performance. This leads to improved feed conversion efficiency and shortened production times, thereby decreasing methane emissions per unit of product, even if absolute emissions remain unchanged (Congio et al., 2018; Hristov et al., 2013; Meo-Filho et al., 2022; Sakamoto et al., 2020).

Methane conversion rate (YM) values ranged from 2.0% to 11.6%, influenced mainly by diet and animal body weight (Johnson and Johnson, 1995). Lima et al. (2022a) reported YM values consistent across treatments (6.2–7.1%), aligning with IPCC (2006) estimates for tropical ruminants (6.5–7.5%). Berça et al. (2019) observed slightly lower YM values (below 5%) across treatments, suggesting potential variability due to local conditions or methodological differences. These findings indicate the need for further research to expand sample sizes and detect significant treatment effects on enteric methane emissions in tropical pastures.

Lima et al. (2022b) underscore the importance of rational nitrogen application in tropical pastures, demonstrating that moderate fertilization doses can increase productivity per area without compromising environmental sustainability. Treatments with 0 and 75 kg N/ha did not differ significantly in GHG emission intensity, confirming fertilization as an effective strategy for sustainable intensification and pasture restoration. Conversely, high N doses provide limited productivity gains but increase risks of nitrogen losses and environmental harm, reinforcing the need for balanced fertilization that optimizes plant absorption, pasture management, and grazing to maintain ecosystem and production sustainability (Bastidas et al., 2024).

5. Limitations and suggestions for future studies

A Marandu grass (*Brachiaria brizantha*) is the most extensively studied tropical forage species in this research area, further investigations are necessary on other forage genera commonly used in production systems, such as *Panicum*.

Research in this field is often hindered by the lack of standardized terminology in forage science, resulting in the use of overlapping or interchangeable terms. Adherence to established standardized vocabularies, such as those proposed by Allen et al. (2011), would improve clarity and comparability among studies.

The limited number of descriptors used in database search queries restricted the retrieval of relevant articles. Consequently, frequent adjustments in search terms were required, complicating efforts at search standardization and potentially reducing the comprehensiveness of literature surveys.

Data on soil carbon stocks and nitrogen balances in nitrogen-fertilized tropical pastures remain scarce across varied experimental conditions. Similarly, there is a notable lack of research involving different grazing animal species, which limits the generalizability of findings.

There are critical gaps regarding the effects of enhanced-efficiency fertilizers, including those with urease and nitrification inhibitors, on forage production and animal performance in tropical pastures. Although nitrogen losses via ammonia volatilization and nitrous oxide emissions have been documented in some studies, investigations that integrate such fertilizers with animal performance metrics in tropical environments are essentially absent.

Finally, studies addressing soil methane (CH_4) and carbon dioxide (CO_2) emissions under nitrogen fertilization regimes—whether in experimental plots or grazing systems—are insufficient for tropical regions. This knowledge gap is significant, given the role these gases play in greenhouse gas balances and climate change mitigation, and thus represents a priority area for future research.

6. Conclusion

This systematic review demonstrates that nitrogen use in tropical pastures has the potential to enhance forage production and animal performance; however, the observed results are highly variable and context-dependent, influenced by factors such as application rates, nitrogen sources, species, soil types, and management intensities. The significant methodological heterogeneity and lack of standardization among evaluated variables limit the ability to integrate findings cohesively, thereby constraining the understanding of the relationships between nitrogen use, productivity, and greenhouse gas emissions.

Strategies involving the splitting of nitrogen rates (20–60 kg ha^{-1}) and synchronizing fertilization with plant demand appear promising for reducing NH_3 and N_2O losses and improving fertilizer use efficiency. Nonetheless, these observations stem primarily from studies predominantly using urea as the nitrogen source, revealing clear gaps in knowledge regarding alternative fertilizer sources across diverse experimental conditions, especially those involving animal performance.

Notably, several important variables, including forage chemical composition and enteric methane emissions, either showed no significant differences across treatments or were insufficiently studied, reflecting data scarcity and limiting strong conclusions in these areas. Additionally, most of the evidence is derived from studies conducted in Brazil, often with short-term follow-ups and incomplete assessments of greenhouse gases, underscoring limitations in geographic representativeness and temporal scope.

Future research should prioritize expanding the evidence base by investigating a wider range of nitrogen application rates and sources, alongside comprehensive assessments of soil CO_2 and CH_4 emissions, enteric methane production, and carbon and nitrogen cycling within the integrated soil–plant–animal system. Moreover, extending investigation to additional forage species beyond *Brachiaria brizantha* and *Panicum maximum*, as well as incorporating other important tropical grazing animal species such as small ruminants (sheep and goats), will be essential. Such approaches will broaden the evidence base across diverse production systems, supporting the development of sustainable and context-specific nitrogen management recommendations for tropical pastures.

CRediT authorship contribution statement

Carolina Marques Costa Araújo: Writing – review & editing, Visualization, Validation, Methodology. **Vanessa Zirondi Longhini:** Visualization, Validation, Supervision, Project administration. **Jéssica Gomes Rodrigues:** Writing – review & editing. **Marina Maria Pedrosa Méca Ferreira de Castro:** Writing – review & editing, Visualization. **Hitalo Rodrigues da Silva:** Writing – original draft, Methodology, Formal analysis, Conceptualization. **Gelson dos Santos Difante:** Writing – review & editing, Visualization, Supervision, Project administration. **Francisca Fernanda da Silva Roberto:** Methodology, Formal analysis, Conceptualization. **Marcos Antônio Ferreira Júnior:** Methodology, Data curation, Conceptualization. **Marislayne de Gusmão Pereira:** Writing – review & editing, Methodology. **Denise Baptaglin Montagner:** Supervision, Methodology, Formal analysis. **Luís Carlos Vinhas Ítavo:** Visualization, Validation, Supervision. **Antônio Leandro Chaves Gurgel:** Formal analysis, Data curation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Author contributions

Difante, G. D. S. wrote the original draft. Silva, H. R. D.: conception, revision of the writing and editing. Elaboration and improvement of the protocol: Silva, H. R., Roberto, F. F. D., Ferreira Júnior, M. A., Araújo, C. M. C. Difante, G. D. S., Longhini, V. Z. Selection of studies: Silva, H. R., Roberto, F. F. D., Writing, proofreading and editing: Rodrigues, J. G. Araújo, C. M. C. Pereira, M. D. G. Ferreira Júnior, M. Montagner, D. B., Ítavo, L. C. V., Gurgel, A. L. C., Castro, M. M. P. M., Difante, G. D. S.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.agee.2026.110401.

Data availability

Data will be made available on request.

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