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Review

Ammonia Emissions and Building-Related Mitigation Strategies in Dairy Barns: A Review

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Abstract: In this systematic review, the PRISMA method was applied to examine publications from the last two decades that have investigated the noxious gaseous emissions from dairy barns. The aim was to analyse the outcomes from literature studies estimating the quantities of polluting gases produced in dairy barns, with specific focus on ammonia (NH_3) emissions. The review also explores proposed methods to reduce the associated effects through mitigation strategies. Estimation of NH_3 emissions is significantly influenced by the complex interactions among several factors, including animal management practices, such as controlling animal behavioral activities; manure management, like utilising practices for floor manure removal; the type of structure housing the animals, whether it is naturally or mechanically ventilated; and environmental conditions, such as the effects of temperature, wind speed, relative humidity, and ventilation rate on NH_3 release in the barn. These influential components have been considered by researchers, identifying targeted mitigation strategies. Despite growing attention to the issue, gaps in the scientific literature were identified and discussed, particularly regarding the analysis of mitigation strategies and their long-term impacts (i.e., environmental, economic and productivity-wise).

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1. Introduction

The increasing demand for food products (meat, milk, and its derivatives) necessitates efficient management of livestock farming systems to mitigate negative environmental impacts. The formation of polluting gases and their subsequent volatilisation and emission into the atmosphere cause some of these impacts [1].

Methane (CH_4), nitrous oxide (N_2O), carbon dioxide (CO_2), hydrogen sulfide (H_2S), sulfur dioxide (SO_2), and ammonia (NH_3) are all harmful gases in livestock farming. These products are not only detrimental to air, water, and soil, yet also to the health of humans and animals [2]. Consequently, they are a significant cause for concern and are often the subject of research aiming to study impactful events and find valid and environmentally friendly solutions. In detail, NH_3 is not a greenhouse gas, but its transformation into other nitrogen compounds, such as N_2O, can contribute to the greenhouse effect. NH_3 is responsible of eutrophication and soil acidification as well as it is the precursory of particulate matter that affects the respiratory system in humans [3]. The production of this gas in dairy barns primarily occurs through the microbial decomposition of nitrogen-containing compounds in animal waste, particularly urine and faeces.

In the last twenty years, the literature has focused on ammonia concentrations and emissions inside livestock housing buildings, often using case study experiments, various measurement methods, and emission models. Various literature reviews [4–9] have analysed the presence of polluting gases in livestock farming though they did not include the study of strategies to reduce pollution from intensive breeding farms among their research objectives.

Other studies [10,11] have focused only on one specific mitigation strategy (i.e., Precision Livestock Farming (PLF) and acidification, respectively). The review by Hou et al. [12] quantified

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emissions and examined different potential strategies to decrease them, however research results were compiled until 2015, similarly to Loyon et al. [13], who analysed existing Best Available Techniques (BAT). The considerations and conclusions of these publications need to be updated to reflect new knowledge and scientific innovations, particularly regarding the sustainability of feasible practices.

Based on the literature analysis above described, currently, there is no updated systematic review in the literature that simultaneously improves the understanding of the formation and development processes of harmful gases in barns, related emissions, and the variables that influence them while identifying techniques to mitigate their impacts.

The study aims at filling this gap in the literature, for the specific case study of NH_3 in dairy houses and the focus on building design and management. The objectives are (i) to give an overview of the outcomes of various scientific studies that have been conducted until now; (ii) highlight common deductions and any heterogeneity in results, thus; (iii) offering a valid and updated basic knowledge for reference and further investigation on globally significant themes such as caring for and respecting the planet and addressing pollution, conforming to the objectives outlined in the “Agenda 2030” [14].

2. Materials and Methods

The PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines [15] were used to conduct this systematic review, considering mitigation strategies and examining the scientific literature on the concentrations and emissions of polluting gases inside structures for dairy cattle farming.

The structured approach of PRISMA provides clarity and transparency, ensuring systematic identification, screening, and inclusion of relevant studies, compared to other reviews models. In detail, PRISMA's rigorous methodology enables comprehensive synthesis and analysis of evidence, facilitating robust conclusions and informed decision-making, compared to the qualitative synthesis of Traditional narrative review or the conceptual perspective of the Critical review method. By adhering to PRISMA guidelines, bias can be minimised and reproducibility enhanced.

The research was carried out utilizing the "Scopus" bibliographic database. Specific combinations of keywords were employed to limit the analysis of the state of the art and highlight only publications deemed relevant and useful for the review's purpose. The Scopus keywords used were selected from Title or Abstract or Keywords of the papers and included: " (dairy OR cattle OR cows) AND (ammonia OR NH_3) AND emission* AND (buildings OR barns OR housing) AND (mitigat* OR strateg* OR floor OR ventilat*)". This combination led to a total of 301 documents.

Inclusion and exclusion criteria were then used to narrow down the literature selection. The results were limited to articles or reviews (document type) written in English, and with a publishing year limitation of the last 20 years to provide an updated literature analysis. Furthermore, subject area was limited to areas such as Agricultural and Biological Science, Environmental science, and Scopus Keywords limitations were applied to avoid unrelated words such as poultry or swine, and out of the scope topics such as recycling or climate models, and many more.

No limitations were set regarding the analytical approach and methods used, as well as the geographical coverage. These limitations reduced the number of publications from 301 to 225. In detail, with regard to the analysis of gas concentrations in livestock buildings, only publications specifically focused on dairy cattle farms (or dairy cattle and other species when considered in the same work) were selected. The focus of the study was set more on the analysis of mitigation methods related to livestock housing than on the metabolic state of the animal and its diet. Therefore, only scientific papers that investigated NH_3 production (or NH_3 and other pollutant gases, if present in the same study), estimated emissions and evaluated techniques and methods for mitigating environmental impacts, primarily from the perspective of housing design and management, were considered.

From the 225 papers, a further refinement based on the specific aim of this review produced a set of 21 papers. Subsequently, in line with the objectives of the review, the research and literature analysis were extended through citation searching, which identified 6 additional documents specifically addressing emission factors (EFs) and mitigation strategies (Figure 1).

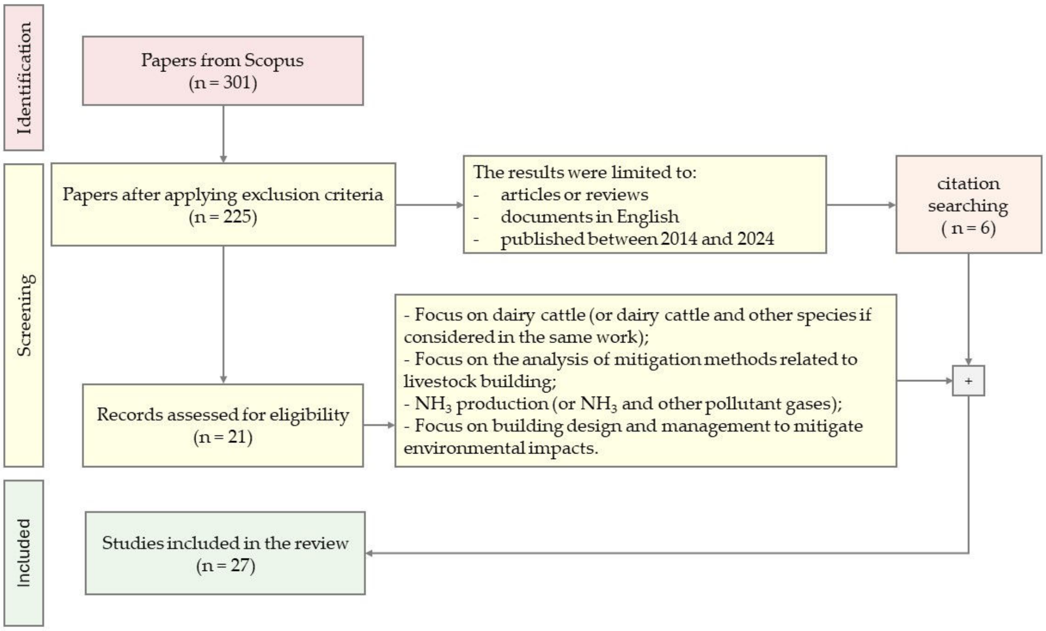

Figure 1. – Flowchart of the PRISMA method concerning the literature considered.

3. Results

Based on the described methodology, a group of 27 studies was analysed in this systematic review, consisting mainly of scientific articles (64%), meta-analyses (16%) and reviews (20%). The research methods used in these studies included conceptual studies (50%), where primary data sources were derived from existing scientific literature and concepts, and empirical studies (50%), where information was obtained from field measurements and data collected through direct observation of phenomena. Geographically, the studies covered various countries in Europe [16,17], Asia [18,19] and North America [20,21] (Figure 2).

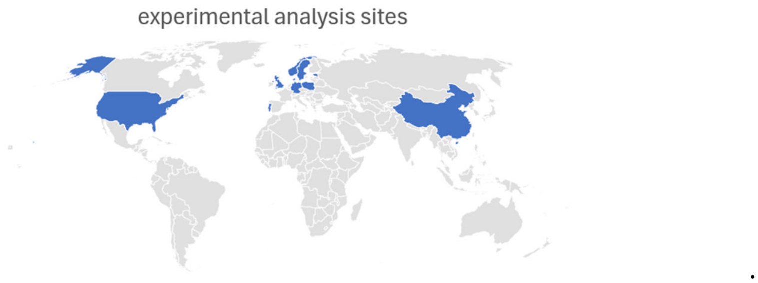

Figure 2. – This map provides a visual context to understand the scope and distribution of selected research carried out in various regions of the world.

The reviewed studies dealt with concentrations of gases considered harmful to the environment and health, with a particular focus on NH_3. They analysed EFs and emission rates within livestock buildings and proposed sustainable solutions to limit the resulting pollution.

Publications were subdivided into two clusters. The first cluster included studies that analysed and quantified NH_3 production and emissions. Through a review of the state of the art of experiments and estimation models, these studies evaluated emission rates and factors. This cluster allowed the

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examination of the relationships between emissions and the livestock environment, climatic conditions [22,23], and house management [24]; however, their influence is consistently evaluated at the building level, as it represents the core focus of the study.

In the second cluster, the review focused on strategies [12], technologies [10] and materials [16] that have been studied to reduce the negative impacts of livestock farming.

3.1. Investigation of potential factors influencing emissions, examination of concentrations within the barn, and estimation of ammonia dispersals

Various studies [12,18,25] have focused on the quantitative assessment of NH_3 emissions from livestock housing, as well as from manure storage and its final application to the soil. In this review, the phase of NH_3 production that takes place inside the livestock building was particularly considered and analysed (Table 1).

Table 1. Significant quantitative data from research studies of cluster 1.

References	Farm type	Range of NH_3 emissions in g AU^{-1} d^{-1} (*'AU' refers to Animal Unit equalling 500 kg body mass)*
Zhang et al. (2005)	Natural ventilation:	
	scraped solid floor	8.2 – 69.0 g AU^{-1} d^{-1}
	flushed solid floor	
	scraped slatted floor	2.7 – 24.5 g AU^{-1} d^{-1}
	flushed slatted floor	10.9 – 61.7 g AU^{-1} d^{-1}
Sanchis et al. (2019)	Natural ventilation:	
	scraped solid floor	2.02 – 111.3 g AU^{-1} d^{-1}
	flushed solid floor	11.1 – 138.9 g cow^{-1} d^{-1}
	scraped slatted floor	25.6 – 102.5 g AU^{-1} d^{-1}
	Mechanical ventilation:	
	scraped slatted floor	15.0 – 18.0 g AU^{-1} d^{-1}
Qu et al. (2021)	Ventilation:	
	unspecified	
	Flooring and manure handling:	
	scraped solid	3.6 - 106 g AU^{-1} d^{-1}
	scraped slatted	23.8 – 27.1 g AU^{-1} d^{-1}
	flushed solid	8.7 – 109.4 g AU^{-1} d^{-1}
	flushed slatted	18.4 – 38.4 g AU^{-1} d^{-1}
Wu et al. (2012)	ventilation: natural	22.5 – 96.3 g AU^{-1} d^{-1}
	flooring: slatted	
	manure handling: scraped	
Tabase et al. (2023)	Natural ventilation:	
	Scraped slatted	23.52 – 38.64 g AU^{-1} d^{-1}
	Mechanical ventilation:	
	Scraped slatted	163.2 – 463.2 g AU^{-1} d^{-1}
Wang et al. (2016)	ventilation: natural	15.4 – 22.8 g AU^{-1} d^{-1}
	flooring:	
	unspecified	
	manure handling: flushed	

 doi:10.20944/preprints202406.1887.v1

Zou et al. (2020)	ventilation: natural	24.0 – 56.6 g AU^{-1} d^{-1}
	flooring:	
	unspecified	
	manure handling: scraped	
Saha et al. (2014)	ventilation: natural	5.5 – 106.1 g AU^{-1} d^{-1}
	flooring: solid	
	manure handling: scraped	
Hempel et al. (2016)	ventilation: natural	0.0 – 96.0 g AU^{-1} d^{-1}
	flooring: unspecified	
	manure handling: unspecified	
Ngwabie et al. (2011)	ventilation: natural	9.6 – 36.0 g AU^{-1} d^{-1}
	flooring: solid	
	manure handling: scraped	
Maasikmets et al. (2015)	ventilation: natural	tie housing cow building: 6.4 ± 0.47 g AU^{-1} d^{-1}
	flooring: solid	loose housing cow barn: 7.8 ± 4.01 g AU^{-1} d^{-1}
	manure handling: removed by tractor	
Bougouin et al. (2016)	Natural ventilation:	
	Scraped solid	9.1 – 108.4 g AU^{-1} d^{-1}
	Scraped slatted	18.5 – 128.1 g cow^{-1} d^{-1}
	Flushed solid	41.3 – 131.0 g AU^{-1} d^{-1}
	Flushed slatted	29.8 g cow^{-1} d^{-1}
	Mechanical ventilation:	
	Scraped solid	8.0 g AU^{-1} d^{-1}
Gilhespy et al. (2006)	ventilation: natural	8.1 – 24.1 g AU^{-1} d^{-1}
	flooring: solid	
	manure handling: scraped	
Rzeźnik et al. (2016b)	ventilation: natural	
	flooring: slatted	
	Manure handling:	
	stored under slatted floor	12.5 – 17.5 g AU^{-1} d^{-1}
	scraped	12.2 – 24.0 g AU^{-1} d^{-1}
	removed by tractor	6.0 – 22.0 g AU^{-1} d^{-1}
Pereira et al. (2010)	ventilation: natural	
	Flooring and manure handling:	
	Scraped solid	65.8 g AU^{-1} d^{-1}
	Flushed slatted	29.9 – 35.3 g AU^{-1} d^{-1}
Rzeźnik et al. (2016a)	ventilation: unspecified	26.7 g AU^{-1} d^{-1}
	flooring:	
	Scraped solid	0.1 – 1.7 g AU^{-1} d^{-1}
	Scraped slatted	
Hassouna et al.* (2022)	Natural ventilation:	
	Flooring:	
	Slatted floor	3.36 – 89.2 g AU^{-1} d^{-1}
	Solid floor	1.72 - 99.7 g AU^{-1} d^{-1}
	Mechanical ventilation:	
	Flooring:	
	Slatted floor	0.04 - 98.8 g AU^{-1} d^{-1}

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	Solid floor	0.05 – 59.3 g AU^{-1} d^{-1}
	Manure handling: unspecified	
	**This article contains the description of a global database that indicate NH_3 emission values expressed as % of the total number of values for each gas analysed. The reported ranges have been derived from the 'DATAMAN' database* [26] *accessed at https://www.dataman.co.nz/DataManHousings.*	
Cinar et al., (2023)	Ventilation, flooring and manure handling: unspecified*	0.0 - 146.7 g AU^{-1} d^{-1}
	** This article states that NH_3 emissions differ between types of housing, but not between types of flooring.*	
Poteko et al., (2019)	ventilation: unspecified	
	flooring:	
	solid	1.1 – 191.2 g AU^{-1} d^{-1}
	slatted	4.0 – 85.0 g AU^{-1} d^{-1}
	manure handling: unspecified	
Sommer et al., (2019)	Ventilation and manure handling:	
	unspecified	
	flooring:	
	solid	12.8 – 55.4 g AU^{-1} d^{-1}
	slatted	0.8 – 88.0 g AU^{-1} d^{-1}

Table 1 shows the results of the studies analysed in this review paper, and in some cases the values of the NH_3 emission ranges taken from the original data reported, expressed in "LU" (Livestock unit) or "HPU" (Heat production unit), were converted into values expressed in g AU^{-1} d^{-1} (where animal unit AU is equivalent to 500 kg body mass).

It is well-documented in the scientific literature that various factors must be considered when evaluating the dynamics that promote ammonia emissions. These factors include, for instance, the type of diet administered to the animal, milk production, cattle breed, and the methodology and instrument used to measure gas concentrations [27]. Nonetheless, in this study, particular attention has been given to building-related factors, which, according to the current state of the art, are the most influential. These include barn ventilation type, the category of barn and the technological features of the structure, flooring type, and the strategy for cleaning the barn floor [7,23,28–31].

In order to be able to identify under which conditions the lowest emissions occur, a comparative analysis was carried out between: NV barns with solid flooring and scraper cleaning system, NV barns with slatted flooring and scraper cleaning system, NV barns with solid flooring and flushing cleaning system, and NV barns with slatted flooring and flushing cleaning system (Figure 3).

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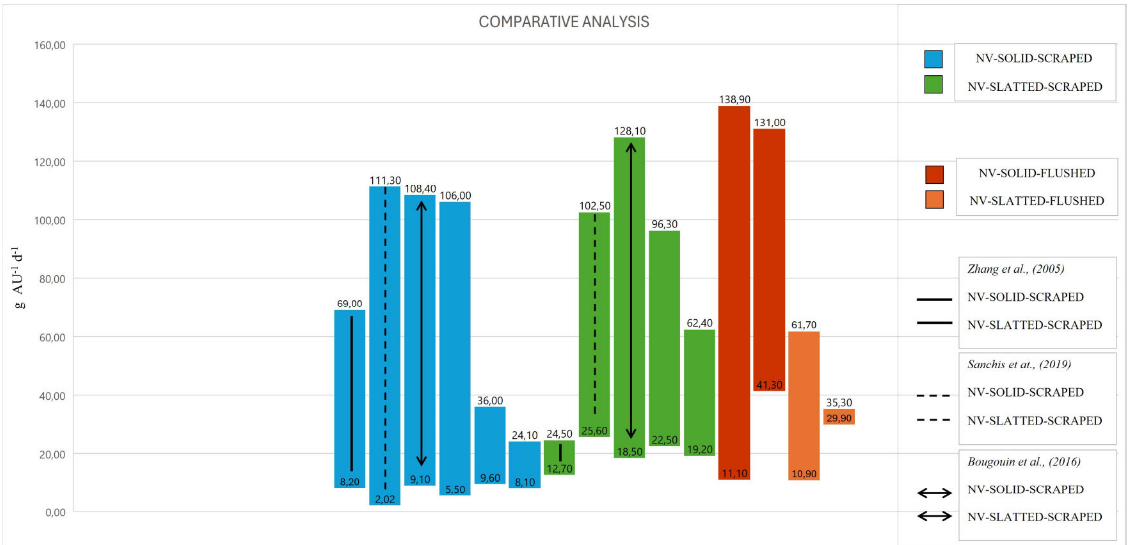

Figure 3. – Comparative analysis among different experimental conditions for manure handling and floor typologies, in naturally ventilated buildings. Experiments having the same flooring and manure handling conditions are indicated with a specific pattern to facilitate comparisons.

It is important to point out that the results presented take into account different studies that certainly have differences among them, in terms of experimental methodology, location of the study site, different intervals and frequencies of floor cleaning, and different methodologies and tools for surveying barn emissions [30,31]. Therefore, comparisons among these values should be carefully evaluated. In order to analyse the experiments that compared the same flooring and manure handling conditions (i.e., NV-slatted-scraped and NV-solid-scraped), emission intervals were highlighted in Figure 1 with the same pattern for the same experiment.

From the results of these analyses, it can be observed that generally NH_3 emissions are lower when there is slatted floor, compared to when there is a continuous type flooring in the barn. When the scraper is used to clean the floor, there seems to be no substantial difference between solid and slatted floor; however, when the flushed system is used, the emissions are lower with the slatted floor.

It is important for future research to deal with the standardisation of results, through the use of databases or precise standards of experimental test execution, along with statistical analyses to corroborate the conclusions drawn from the analyses.

To achieve a thorough understanding of the results, several factors that have a significant influence on the estimation of the NH_3 emissions must be taken into account. The main determinant is the decomposition of urea excreted in animal urine, which can lead to soil acidification and alter the balance of terrestrial and aquatic ecosystems [16]. Among the publications reviewed, a significant group observed phenomena that directly affect EFs and determined emission rates.

The purpose of the studies by Sanchis et al. [7] and Qu et al. [5] was to quantitatively define the effect of temperature, wind speed, relative humidity, and ventilation rate on NH_3 release in the barn, conducting a meta-analysis. Different climatic conditions (i.e., warm, transition and cold) and barns (i.e., naturally-ventilated (NV), mechanically-ventilated (MV) were studied. The analysis of EFs and rates showed a significant effect of temperature, while neither wind speed nor relative humidity had a statistically significant effect on NH_3 emissions.

Both publications claim that NH_3 emissions increase with increasing air temperature. These results differ from those by D'Urso et al. [32], who suggested that relative humidity is a conditioning factor in addition to air temperature. A more humid environment can contribute to NH_3 formation through processes such as urea hydrolysis in urine. Flight speed can reduce local concentrations but contributes to gas dispersion and dilution in the environment.

 doi:10.20944/preprints202406.1887.v1

Similar assessments were found in the study by Wu et al. [23], who measured NH_3 concentrations in two semi-open dairy barns. A multiple linear regression model was used to describe the relationships between NH_3 emission and influencing factors such as wind direction, wind speed, outside air temperature, inside air temperature, and inside air speed. It was found that an increase in wind speed has a positive effect on NH_3 emissions, as increased ventilation promotes dispersion into the environment. An increase in external air temperature also affects the increase in emissions, as higher temperatures favour biochemical processes that contribute to the emission increase. Despite the individual intensifications of wind speed and outside air temperature, together they can have a negative effect on NH_3 emissions.

These results are confirmed by two studies on different types of livestock buildings, i.e., NV and MV structures [20,33]. Tabase et al. [33] analysed internal climatic conditions in buildings, both MV and NV, focusing on variables such as temperature, humidity, and air exchange rate. This study demonstrates that high relative humidity contributes to increased NH_3 volatilization in poorly ventilated structures, and diurnal variations in air exchange rates reduce gas concentrations in buildings. Additionally, this study makes assessments regarding manure management, stating that this practice significantly influences emissions. Specifically, it was found that floor cleaning with robotic scrapers reduces NH_3 emissions more than manual cleaning. In the study by Wang et al. [20], the distribution of NH_3 concentration was evaluated by using low cost and accurate instruments in a NV barn, finding dependence on environmental factors such as wind speed and prevailing wind direction, sunlight, and the cows' activity in the barn.

Other studies, considered in this review [19,22,34], detected NH_3 concentrations and estimated emission rates (using different methodologies such as the CO_2 mass balance method or regression models). They again concluded that gas emissions are correlated with temperature and relative humidity. Based on these studies, it has been possible to highlight an amplification of NH_3 emissions during the day, correlated with stronger winds and lower humidity, and that a lower internal temperature significantly reduces emissions according to an exponential function [34]. A further outcome was the significant seasonal variation in NH_3 emissions, which are higher in spring and summer than in winter, with peaks linked to animal activity during meals and milking routines [22].

The effects of animal activity and air temperature inside the barn were analysed in the study by Ngwabie et al. [35] who carried out the measurements of in a NV building that had a free-stall system with a solid concrete floor mechanically cleaned every hour. This publication claims that NH_3 emissions increased as the indoor temperature of the building increased, since the temperature of the manure is critical for emissions. Higher indoor temperatures probably lead to higher NH_3 emissions because of the relationship between air and manure temperatures and the relationship between air temperature and ventilation rate through natural convection.

Wind and relative humidity are also conditioning factors; in fact, wind can affect the natural ventilation of the building, contributing to the dispersion of gases emitted by animals and manure; relative humidity can influence the formation of ammonia and other gaseous compounds within the building, as high humidity conditions can promote certain chemical reactions and emission processes. In addition, it was observed that NH_3 emissions showed significant variations throughout the day, with two peaks probably related to feeding routines, which supports the thesis that cattle activity is an influential element in gas production.

Similar findings were obtained in the studies carried out by Maasikmets et al. [25] and Bougouin et al. [4], who employed modeling to quantify the main relationships between EF and factors influencing. Maasikmets et al. [25] stated that NH_3 emissions from livestock production result from a complex intertwining of various factors related to animal and manure management, the type of facility housing the animals, and environmental conditions. According to previous studies it was observed that the rate of NH_3 emission depends on temperature, with lower emissions occurring during cooler periods, such as autumn. Two farms were selected for the experiment: the first with fixed housing and a solid manure system removed three times a day, and the second with free stall housing and a liquid manure system removed several times a day through channels and pumps. Gases were measured at the floor surface and, considering temperature and relative humidity, the

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EFs for NH_3 was highest in the fixed housing barn, where cattle were kept on straw beds mixed with manure. The reasons for this difference could also include the feeding management.

Bougouin et al. [4], showed a positive correlation between outdoor temperature and NH_3 emissions, with a tendency for emissions to increase as outdoor temperature increases. In particular, NH_3 emissions were found to be higher during periods of higher temperatures, such as in summer. But unlike previous studies in this trial, it was found that wind speed and relative humidity had no significant effect on NH_3 emissions.

It has also been observed that barns with continuous floors have higher NH_3 emissions than those with slatted floors. In barns with continuous floors, this is due to stagnation of urine and faeces mix, whereas in slatted barns, urine can flow through the cracks and separate from faeces, thereby reducing NH_3 production.

Studies conducted by some authors [24,36] investigated the management practices of barns. However, they use different approaches and methodologies to achieve their results. In detail, Gilhespy et al. [24] examined the relationship between emissions and time cattle spend in barns, quantifying NH_3 losses from livestock housing over a measurement period of about one year. It was found that NH_3 loss was not directly proportional to the amount of time cattle spent in the polytunnel utilised in the experiment. Emissions were higher when calculated over 24 hours of measurement than when calculated over 48 hours, because emissions continued after the animals were moved from the polytunnel, and emission rates decreased over the subsequent 24 hours. As a result, emissions as a percentage of TAN emitted decreased with increasing occupancy. To significantly reduce airborne NH_3, the research concluded that cattle should not occupy pens for more than six hours. Rzeźnik et al. [36] instead, considered and compared different manure removal systems, building types and resting areas. The evaluation of the results showed the dependence of emissions on these factors. It was found that barns with gravity ventilation systems and partially controlled side openings by curtains had lower NH_3 emissions than barns with windows that could be opened. Furthermore, barns with slatted floor manure removal systems had lower NH_3 emissions than barns with scraper or chain manure removal systems.

Assessing NH_3 emissions in livestock housing systems, by focusing on the main types of open housing buildings with natural ventilation, was the aim of the studies by Pereira et al. [37] and Zhang et al. [38]. Differences between the three buildings studied included variations in stall layout, floor type, ventilation opening placement, manure management practices and overall size. It was found that NH_3 emissions varied considerably depending on the type of building as well as the management practices adopted; the differences observed could be attributed to various structural, climatic and management factors specific to each building. These differences were also observed in the review by Rzeźnik et al. [6], which examined research articles containing emissions data published between 1997 and 2015. The study shows that livestock housing systems can have a significant impact on gas emissions. It mentions systems with litter and systems without litter (with fully or partially slatted floors). It was found that litter-free housing is characterised by lower NH_3 emissions, but also by lower animal welfare standards compared to litter systems.

Ventilation also influences emissions, as it helps removing moisture and heat from livestock buildings, thereby affecting air quality. The study by Rong et al. [39] analysed this influential factor, studying the impacts of climate parameters on gaseous emissions, air exchange rate and concentrations in a dairy building with hybrid ventilation. The results showed that the hybrid ventilation system collected 64-83% of NH_3 emissions and 10-50% of CH_4 emissions, thus helping to reduce emissions compared to NV buildings. In addition, it was found that NH_3 emissions through natural ventilation were about 60% lower than the values reported in the literature.

Recently, scientific studies have focused on investigating EFs and creating EF databases. Sommer et al. [8] discussed the development of new EFs for NH_3 derived from manure management. Data from 276 studies, mainly from peer-reviewed scientific journals, were used to calculate new EFs. The EMEP/EEA Air Pollutant Emission Inventory Guide provides EFs to support the compilation of emission inventories. New EFs have been developed for different phases of manure management, showing a wide variability and highlighting the influence of many factors such as management

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practices, animal species, climate and housing conditions. The adoption of these new EFs will influence national NH_3 emission estimates, as variations in EFs will affect the estimation methods used in national inventories.

Hassouna et al. [40] have developed a global database (i.e. the DATAMAN Housing and Storage databases) of EFs for NH_3, CH_4 and N_2O from livestock housing and manure storage. These EFs were provided to improve the accuracy of national inventories, conduct environmental assessments, and identify mitigation techniques and influencing parameters. The DATAMAN database was developed by collecting relevant information for different animal categories, manure types, livestock buildings, outdoor storage and climatic conditions from published studies, conference proceedings and existing databases published between 1995 and 2021. The data were collected and screened for suitability for inclusion in the database. The data were then converted into EFs using a methodology specifically developed for this purpose. The conclusions of the document highlighted the lack of studies in some important livestock production areas and the need to standardise future study approaches and harmonies data from existing studies. In accordance with this statement, Çinar et al. [41] conducted a study with the aim of improving knowledge and reducing uncertainty on the effects of influential factors, analysing the emission rates of NH_3 and GHG collected in the DATAMAN database. This study agreed with the previous one on the importance of collecting data to better understand variations in emissions and increase the accuracy of emission models. This research found that NH_3 emissions are affected by environmental factors such as relative humidity and temperature, as well as by the characteristics of the livestock housing system, showing NH_3 emission rates ranging from 0.036 to 146.7 g N LU^{-1} d^{-1}.

After analysing the results of the aforementioned studies, this review aims at evaluating the correlation between specific factors influencing ammonia emissions within naturally ventilated buildings for dairy cattle housing, and the highest concentration values reported in the literature. The first investigated correlation is between the highest recorded NH_3 concentration values in the barn and the number of animals housed within the barn for various building-related conditions (Figure 4) (Figure 5) (Figure 6).

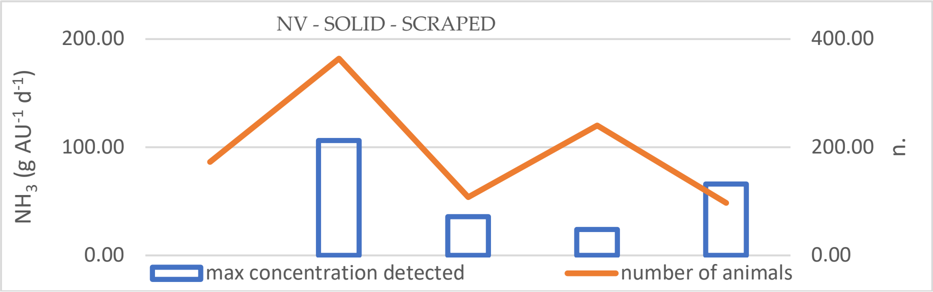

Figure 4. – Correlation between maximum measured values of NH_3 concentrations and number of bred animals in NV barns with solid scraped floor.

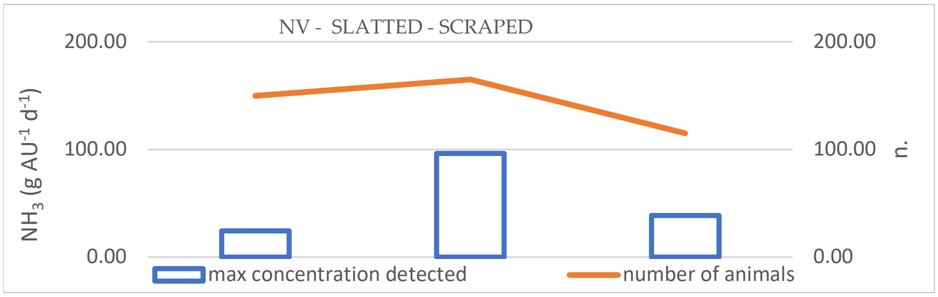

Figure 5. – Correlation between maximum measured values of NH_3 concentrations and number of bred animals in NV barns with slatted scraped floor.

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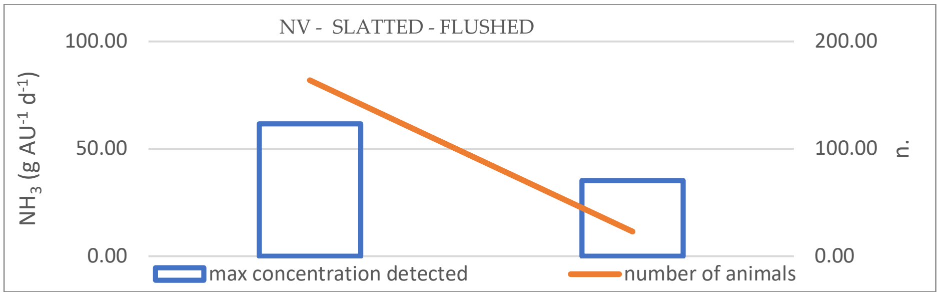

Figure 6. – Correlation between maximum measured values of NH_3 concentrations and number of bred animals in NV barns with slatted flushed floor.

Observing the data, a potential correlation between the number of animals and the peak of recorded values emerged. Specifically, it was noted that the highest the number of animals the highest is the maximum concentration of NH_3.

Equally, when the number of animals decreases, a similar trend was observed in the maximum values of NH_3 concentration.

The second investigated correlation concerned the milk yield and the highest values of recorded NH_3 concentrations in the barn (Figure 7) (Figure 8) (Figure 9).

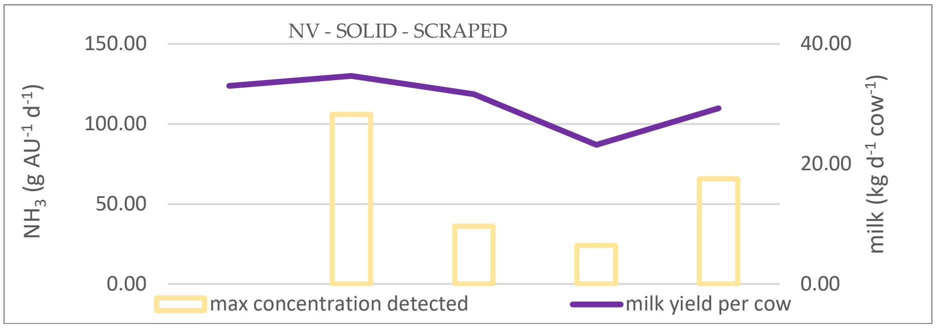

Figure 7. – Correlation between maximum measured values of NH_3 concentrations and milk yield per cow in NV barns with solid scraped floor.

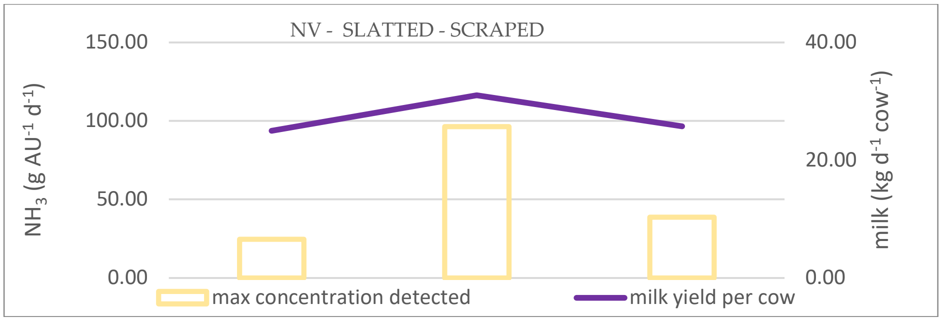

Figure 8. – Correlation between maximum measured values of NH_3 concentrations and milk yield per cow in NV barns with slatted scraped floor.

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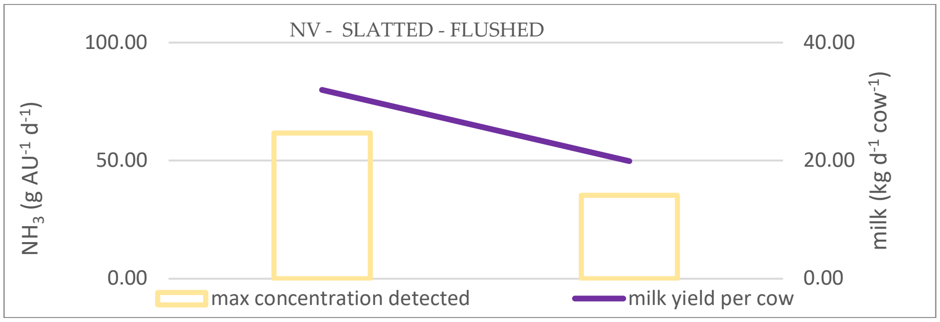

Figure 9. – Correlation between maximum measured values of NH_3 concentrations and milk yield per cow in NV barns with slatted flushed floor.

The data analysis revealed a possible correlation between the number of animals and the maximum recorded values. Notably, when milk yield peaks, the highest concentration value tends to increase. Likewise, as milk yield decreases, the maximum value of concentrations declines.

The last correlation studied was between the highest NH_3 concentration values recorded in the barn and the average temperature measured inside the building (Figure 10) (Figure 11) (Figure 12).

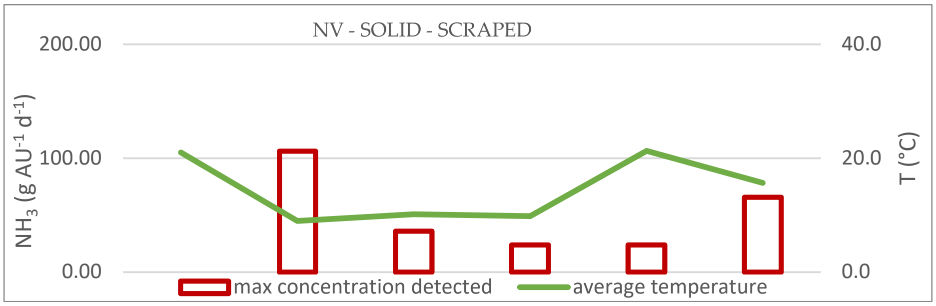

Figure 10. – Correlation between maximum measured values of NH_3 concentrations and average inside temperature in NV barns with solid scraped floor.

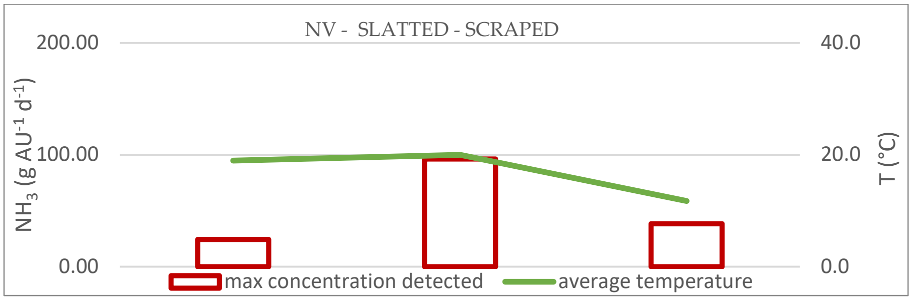

Figure 11. – Correlation between maximum measured values of NH_3 concentrations and average inside temperature in NV barns with slatted scraped floor.

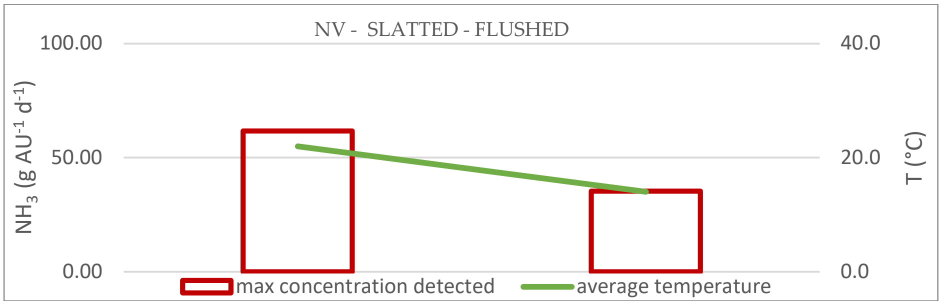

Figure 12. – Correlation between maximum measured values of NH_3 concentrations and average inside temperature in NV barns with slatted flushed floor.

Observing these graphs, although in Figure 10 it appears to be no direct dependency between the maximum recorded value range and the internal temperature, however, examining Figures 11 and 12, it was evident that as the temperature increases, the concentrations also rise, which confirms the assertions of many of the studies described [5,7,19,22,25,34,35,38,41].

These results indicate that ammonia emissions are not uniquely dependent on a specific factor, but rather are the outcome of the interaction of all surrounding conditions. Among these conditions, in addition to those examined in the graphs, factors such as the breed of cattle also play a role [42]. Only 17.6% of the selected articles specified the breed of cattle present inside the barn during the experimental measurements; among these the indicated breeds were: Norwegian red (nrf), Swedish Holstein, Bos taurus, Charolais x Friesian, and Simmental beef cattle.

Another extremely influential factor is the technique used for measuring the concentrations in the barn, along with the choice of instruments, the number of repetitions performed, and the season in which the experimentation was conducted [30] [43]. In particular, several techniques have been used to measure ammonia concentrations. Passive flow samplers were employed by 17.6% of the studies, the photo-acoustic technique by 47%, and electrochemistry by 5.9%. Considering the influence of the type of instrument used, it is important to highlight their detection accuracy. In fact, the study conducted by Calvet et al. [44] provided typical precision values (which may vary for different concentration ranges); these are: 5 - 10 % of magnitude for the technique with passive flow samplers, 2.5% for the photo-acoustic system, and 8% for electrochemical technology.

Regarding the season in which the measurements were conducted, among the articles selected for this review, experiments were most frequently performed during spring and summer, and much less often in winter (Figure 13).

These influential elements (such as the diet administered to the animals) have been thoroughly investigated in specific reviews [4] on livestock emissions. In the following section, the focus of this study is oriented towards the mitigation strategies for NH_3 emission reduction, encompassing both characterization of the influences due to the building itself (e.g., type of ventilation, flooring, and technique for cleaning livestock effluents) and other animal-related influencing factors (e.g., nutrition, and PLF).

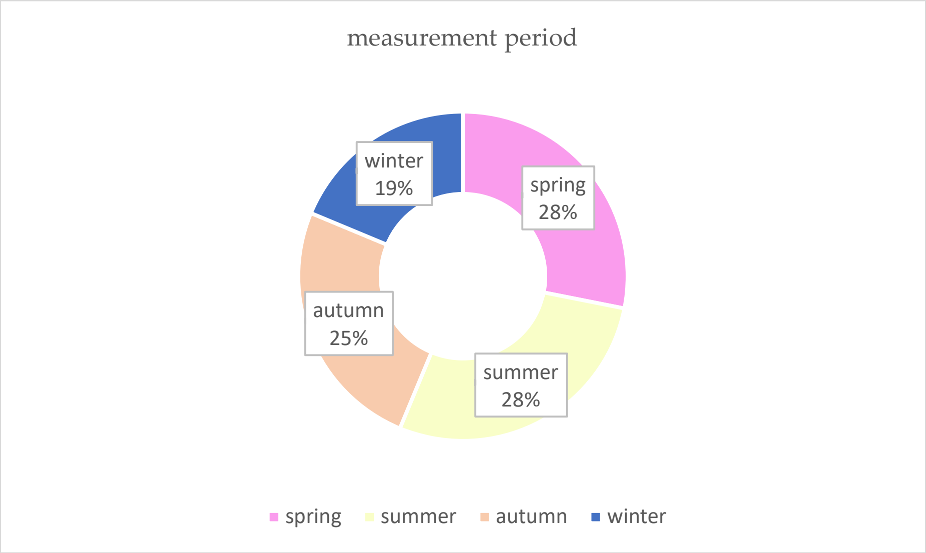

Figure 13. – Seasonal distribution of experimental studies. .

3.2. Mitigation strategy analysis

Among the studies reviewed (Table 2), a large group focused on exploring strategies, technologies and practices to reduce the negative impacts caused by NH_3 emissions. Mendes et al. [17] used a modelling approach to evaluate potential factors to reduce NH_3 emissions in a dairy farm equipped with at least one mitigation technique, comparing it with a barn where no mitigation technique was applied to assess its benefits. The developed model was based on a specific algorithm aimed at identifying the most appropriate abatement management technique among those considered: floor scraping, floor washing with water, different types of flooring, and internal manure acidification. The most effective strategies, in order of efficiency, were found to be manure acidification, floor scraping, and floor washing. The most valid combinations, in order of efficiency, were floor scraping combined with manure acidification (up to 44-49% reduction of emissions), solid flooring combined with scraping and washing (between 21-27% reduction) and floor scraping combined with washing and floor scraping only (17-22% reduction). Acidification, which was considered the most effective strategy in this study, was also investigated by Fangueiro et al. [11]. Acidification involves lowering the pH of the slurry by adding acids or other substances. Several research studies and experiments have shown that lowering the pH changes the composition of the slurry. When slurry is acidified, NH_3 is converted to ammonium, which is less volatile than NH_3, thus reducing emissions to the environment. In addition, acidification can affect the overall production of ammoniacal nitrogen in the manure, further reducing emissions. Although considered a complex practice, acidification can pose threats such as increased solubility of certain mineral elements in manure, thus increasing the risk of leaching. However, if correctly applied, acidification can be an effective strategy to reduce NH_3 emissions and improve manure environmental management.

Table 2. Cluster 2 significant data on the characteristics of the barns and mitigation strategies.

References	Farm type	Mitigation strategies	% reduction
Mendes et al. (2017)	ventilation: natural flooring: solid manure handling: scraped and flushed	· manure acidification · floor scraping · floor scraping and washing · floor design	27% 17% - 22% 20% - 27% -
Fangueiro et al. (2015)	ventilation: not available flooring: not available manure handling: not available	· manure acidification	37%

Hou et al. (2015)	ventilation: natural flooring: solid; slatted and deep litter manure handling: crusting; straw cover; artificial film and acidification	· reduction of the protein content of the animal diet · external slurry storages via acidification · cover of stored manure with straw or artificial film	24 – 65% 83% 78 – 98%
Baldini et al. (2016)	ventilation: natural flooring: solid; rubber matted and slatted manure handling: scraped and flushed	· Feeding alley: · Flushing system (percentage of reduction compared to the worst condition: scraper on concrete floor) · Resting area: - Rubber mat-bedded cubicles (percentage of reduction compared to the worst condition: Straw-bedded cubicles)	80% 20%
Snoek et al. (2017)	ventilation: unspecified; flooring: solid and slatted manure handling: scraped and manually cleaned	· floor design · use of scrapers	- 50 – 70%
Xu et al. (2017)	ventilation: unspecified; flooring: unspecified; manure handling: unspecified	· low nitrogen food (LNF) · manure management	18.9 - 37.3%
Tullo et al. (2019)	ventilation: natural and mechanical; flooring: unspecified; manure handling: unspecified	· precision Livestock Farming (PLF)	27 – 41%

Bobrowski et al. [45] proposed to evaluate the seasonal mitigating effects of a urease inhibitor under practical conditions and provide information on two theoretical application scenarios to estimate an annual scenario. The inhibitor, called "inhibitor K", is described as a ready-to-use pyrrolidone-based chemical formulation. It was manually applied on the surfaces of two dairy sheds for three days during the summer, winter and transition period. The work shows that the use of urease inhibitors in NV dairy barns, in combination with appropriate application, can significantly reduce NH_3 emissions in dairy sheds in all seasons, representing a potential solution to mitigate the environmental impact of such emissions. Another research carried out by Bobrowski et al. [46] suggested that urease inhibitors may be a mitigation solution with lower investment requirements, also in a MV dairy housing system. However, they observe that further research is needed to assess the direct reduction in NH_3 concentrations.

Further valuable insights into mitigation strategies can be derived from a meta-analysis of 126 published studies on manure management at all stages by Hou et al. [12]. Various strategies were considered, including reducing the protein content of animal diets, manure acidification, covering manure with straw or artificial film, compacting and covering solid manure, and manure application by broadcasting, incorporation and injection.

The results showed that managing animal diets and manure acidification were the most effective strategies for reducing harmful gas emissions throughout the livestock waste management chain.

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Furthermore, manure incorporation and covering with straw or artificial film were proposed in this meta-analysis as effective strategies for reducing NH_3 emissions. However, Baldini et al. [16] emphasised the need to regularly renew the bedding of the cubicles to avoid anaerobic conditions in the deeper levels of the straw. In this study, greenhouse gas emissions measured in NV barns with different types of flooring and manure handling systems were studied and defined, focusing on the potential for reducing emissions through the choice of flooring type and manure handling strategies. From the described analyses, it was found that the EFs were higher in barns with solid floors equipped with scrapers, and lower in barns with perforated floors or washing systems for manure removal. These results were attributed to the contact surface between urine and urease in faces, which influenced the percentage of urea effectively converted to NH_3. In addition, scrapers usually leave a thin layer of slurry, which increases NH_3 volatilization by increasing the surface area over which urine is spread and reducing the thickness of urine pools. The study highlights strategies and practices used in barns that have been shown to reduce emissions of harmful gases: frequent and complete removal of manure from floors, including perforated floors; tilting of floors for faster separation of liquid and solid parts; and use of rubber mats instead of concrete floors, coupled with scrapers to increase cleaning efficiency.

However, the study conducted by Chiumenti et al. [47] stated that rubber coated floors showed higher emission rates than concrete floors, both before and after the operation of the robotic scraper.

Snoek et al. [48] evaluated the characteristics of fresh urine pools (i.e., area, depth and resulting volume) in commercial dairy barns and studied how variables such as flooring type, season and manure scraping method influenced these characteristics. Four types of barns were considered for the experiment: the first was the reference situation with slatted floor and manure pit; the second had a fully closed and grooved floor; the third had a fully closed V-shaped asphalt floor; the last had a slatted floor like the first type. It was found that manure scraping can significantly influence the area and depth of urine pools. The type of flooring and the season also influenced the size of the pools. In this study largest and statistically significant puddle areas occurred in the V-shaped, solid asphalt floor. Upon comparing the slatted floor to solid floor configurations, it becomes apparent that the drainage of excreted urine is notably more effective on slatted floors, facilitating its flow into the underlying manure storage system. Slatted and grooved floors could be considered more effective in reducing ammonia emissions than asphalt V-shaped floors. A valid mitigation strategy proposed by the authors was to reduce urine pool sizes and consequently NH_3 emissions by the use of manure scraping practices combined with "Preclean" floor that showed a potential for reduction of urine pools of about 50 - 70% less than just scraping.

According to Xu et al. [18], low nitrogen feeding is the most effective mitigation system and, together with proper manure management, offers the best prospects for reducing total NH_3 emissions and minimising impacts. To reach this conclusion, emission trends over time were analysed to identify factors contributing to emission increases and to identify areas with the highest emissions.

The study by Tullo et al. [10] examined the environmental impacts of livestock practices and discussed the benefits of PLF as a potential system to mitigate environmental risks. PLF is a technology that uses sensors and algorithms to monitor and manage animal production more efficiently and sustainably, aiming to make livestock farming more economically, socially and environmentally sustainable through observation, interpretation of behaviour and individual animal control. The review presents circumstantiated examples of how PLF can contribute to reducing the environmental impact of livestock production, including studies that have used the life-cycle analysis approach to validate the potential of PLF to improve animal welfare, enhance technical performance, and minimise environmental impact. Through a review of the scientific literature, the study concludes that precision farming offers significant benefits in terms of monitoring and control, reducing harmful emissions and improving animal welfare, thereby contributing to making livestock farming more economically, socially and environmentally sustainable.

4. Discussion and future directions

NH_3 emissions from livestock production are the result of complex interactions between several factors, including those related to animal and manure management, the type of structure in which the animals are housed and environmental conditions. For example, animal diet, including protein content and nutrient composition, influences NH_3 emissions as it can lead to higher nitrogen excretion. Certain farming practices, such as the use of bedding, the type of manure management system and even the maintenance of livestock buildings, can also affect NH_3 emissions [21]. Therefore, mitigation strategies typically include measures aimed at manipulating animal diets and adhering to principles of good housing design and manure storage [13].

Among the selected studies, a significant number aimed at quantifying emissions by estimating those using different approaches and computation models. For example, mixed effects linear models, mass balance models based on total NH_3 nitrogen, CO_2 balance models, backward dispersion methods, and equations defined in relation to each individual case study were used. This variety of estimation methods are one of the identified limitations of the research. The lack of uniform data or standardization of emission measurement methods can contribute to significant variability and uncertainty in the results, affecting the validity of the conclusions [44]. The current scientific literature shows gaps on the topic, leading to fragmented, non-linear knowledge that is sometimes lacking in useful insights, such as the consequences related to the economic sustainability of farms or their productivity.

To overcome these limitations, current research is moving towards the creation of databases that can be shared and consulted for experiments, with the aim of improving the representativeness, certainty and generalisability of results [8,40] as well as the use of protocol for estimation [49] and the improvement of the methods for monitoring concentrations [50].

Another gap identified in the reviewed papers is the limited geographical coverage. There are no studies that specifically examine the impact of livestock production in specific geographical areas, such as South America, Africa, Australia, North Asia and the Pacific Islands. Research in climatically extreme parts of the world is particularly lacking. Environmental factors, as highlighted by the results found in the publications selected for this review, are crucial for gas emission and diffusion into the atmosphere. It will be essential to extend the spatial coverage of research, to consider environmental parameters representative of more areas of the planet, and to propose in-shed measurement protocols and emission calculations fine-tuned to specific types of houses and climatic conditions. Furthermore, in order to validate the results of the experiments, it would be appropriate to evaluate study periods and measurements that take into account different periods of the year and, consequently, different meteorological seasons. Stable environmental conditions during the sampling periods could influence the results, leading to imprecise or even incorrect emission estimates.

As delineated in Figure 13, studies have largely neglected year-round estimations of emissions, with only 23.5% of articles conducting measurements across all seasons. Instead, the majority have focused on estimating emissions during warmer periods, given their propensity for heightened concentrations [51] [43]. It is imperative that future research endeavours undertake comprehensive assessments of temperature variations throughout the year to elucidate the various dynamics of ammonia emissions across diverse global regions and seasonal contexts.

As expressed in the scientific publications analysed, other crucial elements to be considered that influence the estimation of emissions are the characteristics of the structures in which the animals are housed and the manure management strategies. The review by Bougouin et al. [4] highlights how emission results vary depending on the type of ventilation or flooring and the manure management strategy. For example, the document cites the study by Aguerre et al. [50], in which in a NV barn with a solid floor, the NH_3 emission calculated by mass balance was 14.1 g cow^{-1} d^{-1}. In contrast, in the study by Bluteau et al. [52], using the same calculation method in a barn with the same characteristics but MV and with a scraper to remove manure from the floor, NH_3 emission was 6.5 g cow^{-1} d^{-1}. When compared to other NV barn with a slatted floor, the emission value was still different.

The importance of livestock management, the diet provided, and how animal behaviour conditions the volatilization and subsequent diffusion of NH_3 have also been addressed. For example, Gilhespy et al. [24] demonstrated the relationship between emissions and the time spent in the barn

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by livestock, highlighting the consequent need to manage animal movements to reduce NH_3. This study found a non-linear relationship between the time spent in the barn and NH_3 emissions. Unlike CH_4, which is closely linked to the presence of the producing animal, NH_3 depends on the mixture of faces and urine, even without the presence of the animal, as its volatilisation occurs after the reaction resulting from the contact of these two elements. This knowledge, together with the results of many other studies [5,11,31,46], confirmed the fundamental importance of manure management in the barn.

The first cluster confirms how one of the influencing factors is air temperature, which is positively correlated with NH_3 emissions. Increases in temperature favour biochemical processes that contribute to increased emissions. Wind speed can have a positive effect on emissions by promoting the dispersion of NH_3 in the environment. Relative humidity has conflicting effects, with some studies claiming that it has no significant effect on emissions, while others suggest that a more humid environment can contribute to NH_3 formation.

Manure management has a significant effect on emissions; for example, cleaning floors with robotic scrapers can reduce emissions more than manual cleaning. The impact of livestock feeding has been studied and it has been found that increasing the crude protein content of the diet and dry matter intake can lead to increased emissions. Building ventilation also affects emissions by helping to remove moisture and heat, thereby affecting air quality. The type of flooring used in barns has also been studied, with continuous floors having higher emissions than slatted floors. Moreover, the separation between urine and faeces reduces NH_3 emissions in dairy farming systems [51].

The results reported by the studies in the first cluster of publications analysed were crucial in this systematic review to provide evidence and quantitative data to support the hypotheses of the mitigation systems. Nevertheless, despite these findings, certain information gaps have been identified among the cited articles. It will be pertinent for future experiments to elucidate influential factors such as bovine breeds and the orientation of barns to assess the impact of natural ventilation on the concentrations observed indoors [53].

The second cluster comprises research aimed at studying the validity, effectiveness, and functionality of tools for mitigating the impacts caused by NH_3 emissions. The evaluated strategies to reduce pollution included materials and designs of barn floors, use of scrapers and frequent washing of surfaces where manure is formed, acidification, diet management, and control of animal behaviour.

It has been observed that while these practices can reduce emissions when used individually, they may not be enough to significantly mitigate their impact on the environment. Therefore, research suggests their combined use.

However, few studies conducted to date have been fully assessed the true sustainability of these solutions. For instance, washing floors with water does not consider the wastage of this precious resource. In the future, it will be necessary to address the challenges related to sustainable water management, such as wastewater treatment and reducing excessive use. Additionally, acidification could have severe consequences, including an increase in H_2S emissions immediately after acidification and the solubilisation of mineral elements that can cause losses through leaching. Additionally, careful, and specialised management is required, which incurs high treatment costs.

For each type of strategy, it is necessary to evaluate both economic and environmental impacts. Although the literature has proposed solutions, such as the BAT, for protecting the environment, future research should focus on investigating the long-term impacts of known strategies from both environmental and economic/productivity perspectives, as well as developing new advanced technologies and sustainable practices to reduce emissions. The possibility of using artificial intelligence and smart systems to design innovative materials that can absorb produced gases can be examined. Additionally, the mitigation potential of waste materials [54] and technologies that have already been studied and tested for reducing emissions of pollutants produced within cities, such as systems of green walls or green roofs [55], should be evaluated; e.g., in the study by Ali Ajami et al. [56] the use of a green wall, or vegetative strip, within the porous wind barrier system was assessed to improve the removal of airborne particles, such as emissions from livestock sheds.

The vegetative strip can help capture suspended material particles, such as adsorbed dust and gases, and dilute the air column through dispersion. In addition, the vegetative strip can increase the open surface area without increasing back pressure, thus improving the overall efficiency of the system in removing harmful emissions.

It is also important to investigate strategies that can significantly reduce pollution and have zero impact themselves not only at farm level, emphasising the utilisation of byproducts and manure from livestock context in a circular economy perspective also at a territorial level [57].

5. Conclusions

Ammonia emissions are a critical consequence of livestock productions and a widely discussed topic in the literature. The analysis of literature studies on NH_3 emissions and mitigation strategies in livestock farming, specifically focused on dairy housing, revealed a complex and multidisciplinary framework.

This PRISMA-based review highlights the following key conclusions regarding NH_3 emissions from livestock production and strategies for mitigation:

- NH_3 emissions from livestock production are influenced by various factors, including livestock management, housing structures, facility maintenance, and environmental conditions. Studies have shown that factors such as ventilation, flooring type, and manure management strategies can have substantial effects on emission levels. Understanding these factors is essential for developing effective mitigation strategies. In detail, manure management is a fundamental element in reducing emissions by using practices such as acidification and solid-liquid separation. The introduction of innovative technologies, e.g., the use of artificial intelligence, has emerged as a potential driver of sustainability.
- Methodological shortcomings depend on the diversity of estimation methods used in research studies, which poses a challenge to comparing results and drawing robust conclusions. The lack of standardised measurement methods contributes to variability and uncertainty in emission estimates. Moreover, shared databases, properly designed and maintained, are essential to guarantee the comparability of results across various studies.
- A significant gap in research geographical coverage was registered by this review, particularly in regions such as South America, Africa, Australia, North Asia, and the Pacific Islands. Studies in climatically extreme areas are particularly lacking, hindering a comprehensive understanding of NH_3 emissions globally. A research perspective that covers different regions and climatic conditions is necessary to develop mitigation strategies adapted to specific local needs and climate variables.
- Various mitigation strategies have been explored, including diet management, manure management practices, and animal behavior control. However, research suggests that a combination of multiple strategies may be necessary to achieve significant emissions reductions. Moreover, while mitigation strategies can reduce emissions, their long-term sustainability and economic viability need further investigation. Sustainable water management, the environmental impact of acidification, and the economic feasibility of mitigation practices require careful evaluation.

Future research should focus on evaluating the environmental and economic impacts of mitigation strategies, analysing new technologies, and exploring innovative solutions based on artificial intelligence and green technologies. Emphasizing circular economy principles and territorial-level approaches can further enhance emissions reduction efforts.

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