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Is it possible to combine animal welfare and mitigation strategies? A network analysis

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ABSTRACT

While concerns about the environmental issue intensify, agricultural activities continue to be a significant source of greenhouse gas emissions. Among these activities, those related to livestock farming stands out. Consequently, matters such as climate change and the depletion of finite natural resources need to be addressed while ensuring the global food demand for the future generation. Several surveys focused on finding solutions for these challenges overcoming potential hindrances. Livestock systems are required to address, among other objectives, animal welfare and environmental issues, potentially through a single pathway toward a twofold objective. The aim of this study is to assess whether livestock farmers implement management practices that can achieve a dual objective: enhancing animal welfare performance while simultaneously reducing environmental impact. To this end, the study analyzed 102 papers and conducted both a descriptive analysis and a network analysis to examine the existence of livestock practices serving this dual function since according to our knowledge there are no previous researches covering this analysis. The study followed the PRISMA protocol and used the software Vosviewer. The results underscore the importance of fostering connections between animal welfare and environmentally friendly practices. Developing harmonized strategies that optimize both natural and farm resources is crucial for achieving sustainable agricultural systems.

1. Introduction

In recent years, growing concerns about the environmental consequences of farm management have gained significant attention among policymakers, researchers, and stakeholders worldwide. Numerous studies have identified livestock production as a major contributor to greenhouse gas (GHG) emissions (Llonch et al., 2017; Oettl et al., 2022). These emissions, stemming from various aspects of farm operations, generate adverse environmental externalities (Yi et al., 2020; Manzano and White, 2019), thereby reinforcing the established link between livestock farming, global warming, and climate change.

In particular, elevated emissions of ammonia (Tullo et al., 2019; Mostafa et al., 2020) and methane (Bačėninaitė et al., 2022) from livestock operations significantly exacerbate climate change, with cascading effects on human health, animal health and ecosystem stability (Perry and Grace, 2015; Mehrabi et al., 2020; Johnson et al., 2022). This situation forms a vicious cycle in which climate change further intensifies extreme weather conditions, amplifying the environmental stressors affecting farm systems.

Importantly, these environmental stressors not only affect ecological balance but also have direct implications for animal welfare. Heatwaves, cold spells, and unpredictable temperature fluctuations negatively influence livestock behavior (Henry et al., 2018; Chulayo and Muchenje, 2016), welfare status (Adjassin et al., 2020; Herbut et al., 2021), and productive performance (He et al., 2021; Fuquay, 1981). Additionally, there is a link between exposure to high concentrations of atmospheric GHGs and adverse health outcomes in farm animals (Mele et al., 2019).

Given that animals represent the core of livestock systems, these environmental externalities pose a systemic threat, undermining the very foundation of the sector (Small et al., 2021). As noted by Lintner (2020), animal protection laws often cover only the minimum acceptable standards of welfare, leaving significant room for improvement. This highlights the need to explore whether enhanced animal care, both at the individual and group level can be integrated with climate mitigation strategies to simultaneously improve animal welfare and reduce environmental impacts.

The objective of this study is to investigate whether animal welfare practices, implemented within diverse livestock systems, can also

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function as effective components of climate mitigation strategies aimed at achieving environmentally sustainable outcomes (Menardo et al., 2021). To our knowledge, this intersection between animal welfare and environmental mitigation remains underexplored in the literature, with only a limited number of studies addressing this dual challenge (De Boer et al., 2011).

The relevance of this question lies in the fact that, in practice, the two dimensions, animal welfare and environmental mitigation, can sometimes be in conflict (Aluwong et al., 2011). Indeed, some studies have shown that certain mitigation strategies, which involve changes in farming practices, may appear beneficial but, in reality, could have uncertain or even negative effects on both human and animal welfare (Shields and Orme-Evans, 2015; Sharma, 2022). For example, the intensification of production, while aimed at improving efficiency, may increase the risk of production-related diseases such as mastitis, lameness (Herzog et al., 2018), tail injuries (D'Eath et al., 2014), infectious bovine keratoconjunctivitis, and Bovine Spongiform Encephalopathy (Evans, 1999), among others, which contradicts the principles of animal care (Dewell et al., 2014; Hasler and Howe, 2012). Therefore, if it is beyond doubt that climate change is one of the most urgent environmental issue of our time to address, on the other side, the ethical considerations involving the maintenance of animal welfare should not be sacrificed (Nordgren, 2012), although this sometimes occurs (Peden et al., 2018b). In contrast, no environmental impact mitigation measures should imply any potential trade-offs for animal welfare (Herzog et al., 2018).

This point of view also reflects the concept of sustainability as applied to livestock systems, understood in its various dimensions, with environmental and ethical sustainability being particularly relevant in this context (Zarbà et al., 2021). These declinations in fact imply the simultaneous pursuit of welfare and mitigation of environmental impacts. From this perspective, production systems must meet the needs of the current generation without compromising the ability of future generations to meet their own needs (Sturaro et al., 2012) and should adopt a holistic approach (Naranjo et al., 2023).

Currently, animal-based food systems are a vital source of nutrition for the majority of the global population (Makkar, 2016; Mpofu et al., 2023). As the world population is projected to reach approximately 8.6 billion by 2032 (OECD/FAO, 2023), the demand for animal products will remain substantial. Therefore, the development of sustainable livestock systems becomes crucial, particularly in regions where rural communities depend heavily on livestock for subsistence and live in environments unsuitable for crop cultivation. In wealthier nations, although reducing the consumption of livestock products is feasible and even advisable from a sustainability standpoint, overall consumption levels remain high (Faisal et al., 2021; Wegner et al., 2022).

Against this backdrop, mitigation has emerged as a central concern in ensuring the long-term sustainability of livestock production. It is essential to identify and promote farming practices, technologies, and policies that can reduce environmental impact while simultaneously enhancing animal welfare. Only by adopting such integrated strategies, the livestock sector transition toward a more sustainable and ethically responsible future can happen.

2. Methods

The methodology employed in this study is based on a meta-analytical approach supported by a comprehensive literature review. The objective is to assess the potential impact of integrated practices that simultaneously address environmental mitigation and animal welfare within livestock sectors and systems. The present research is primarily grounded in a bibliometric review, and is further enriched by a qualitative synthesis. To ensure methodological rigor and transparency, two distinct approaches were adopted: the PRISMA protocol for systematic reviews (Page et al., 2021), and a co-occurrence analysis using VOSviewer software, which enabled the identification of thematic clusters and relationships among key concepts in the relevant scientific literature.

2.1. Data base selection: PRISMA

This systematic literature review follows the qualitative Preferred Reporting Items for Systematic Reviews and Meta-analyses (PRISMA) guidelines (Shamseer et al., 2015; Page et al., 2021b). A pre-established chronological and conceptual protocol (Sarkis-Onofre et al., 2012) was used to ensure transparency, replicability and scientific rigor in the articles collection process (Karimi et al., 2026) (Fig. 1). To capture the scope of global scientific research, the core collections of Elsevier Scopus and Web of Science (WOS) were selected as the most suitable databases. These platforms provide a large high-quality sample of journals relevant to this study. In contrast, Google Scholar was excluded because it indexes many non-scientific publications, and PubMed was deemed unsuitable as its focus is limited to "biomedical literature" (Bellia et al., 2022), although this could be considered a limitation.

First, the thematic focus of the present research is on the potential of animal welfare practices adopted in livestock systems to mitigate the environmental impact (Identification phase).

After testing various search strings, the final keywords selected to develop the research were ["mitigation*" and "livestock*" and "animal welfare*"]. The final article collection took place on April 11 2024. The Screening step typically entails a data cleaning process to exclude duplicates and to include only articles and review in all language in order to consider literature with highest visibility within the scientific community (Li et al., 2022). Another phase commonly associated with the PRISMA method is the Eligibility (Domínguez-Solís et al., 2025; Fagbohun et al., 2026; Ordoñez et al., 2024), however, in the present research it did not find application. This decision to omit this stage depends on the circumstance that the methodological structure followed for the present work combined the data processing developed with VOSviewer (Esfahani et al., 2021; Norouzi et al., 2021). This approach relies on an algorithm to select the data, eliminating the need for a separate eligibility phase. So, none articles were excluded and all the 119 articles (Appendix A) represented the universe data of the present analysis (Included).

2.2. VOSviewer co-occurrence analysis procedure

The free JAVA-based software VOSviewer, developed in 2009 by Van Eck and Waltman (2010) at the Centre for Science and Technology Studies (CSTS) at Leiden University in the Netherlands, for creating maps based on network data (Van Eck and Waltman, 2014) supported the following part of the present analysis. This tool processes bibliometric data (Damar et al., 2018) and enables the visualization of the relative network maps derived from scientific publication by combining many factors through a quantitative method (Esfahani et al., 2021; Norouzi et al., 2021). VOSviewer provides a high-quality overview of targeted research topics through the visual representation of the networks that the three topics investigated, "mitigation*", "livestock*" and "*animal welfare" generate among them and others.

Once elaborated, the map displays distinct nodes and each of them represents a keyword where their different size corresponds to the frequency of that keyword's occurrence, indicating its relative importance. Links among nodes represent the co-occurrence relationships, specifically how many times two keywords appear together, with link thickness reflecting the strength of the relationship.

Combining the two methodological approaches, the keywords, titles of articles and abstracts (TITLE_ABS_KEY), gathered adopting the PRISMA protocol, were imported into the VOSviewer software, Fig. 2 to process the so-called co-occurrence network map of the most frequent terms of all selected articles from the databases under consideration, spanning all available search periods (1999-2023).

The scientific mapping are spatial representations displaying the

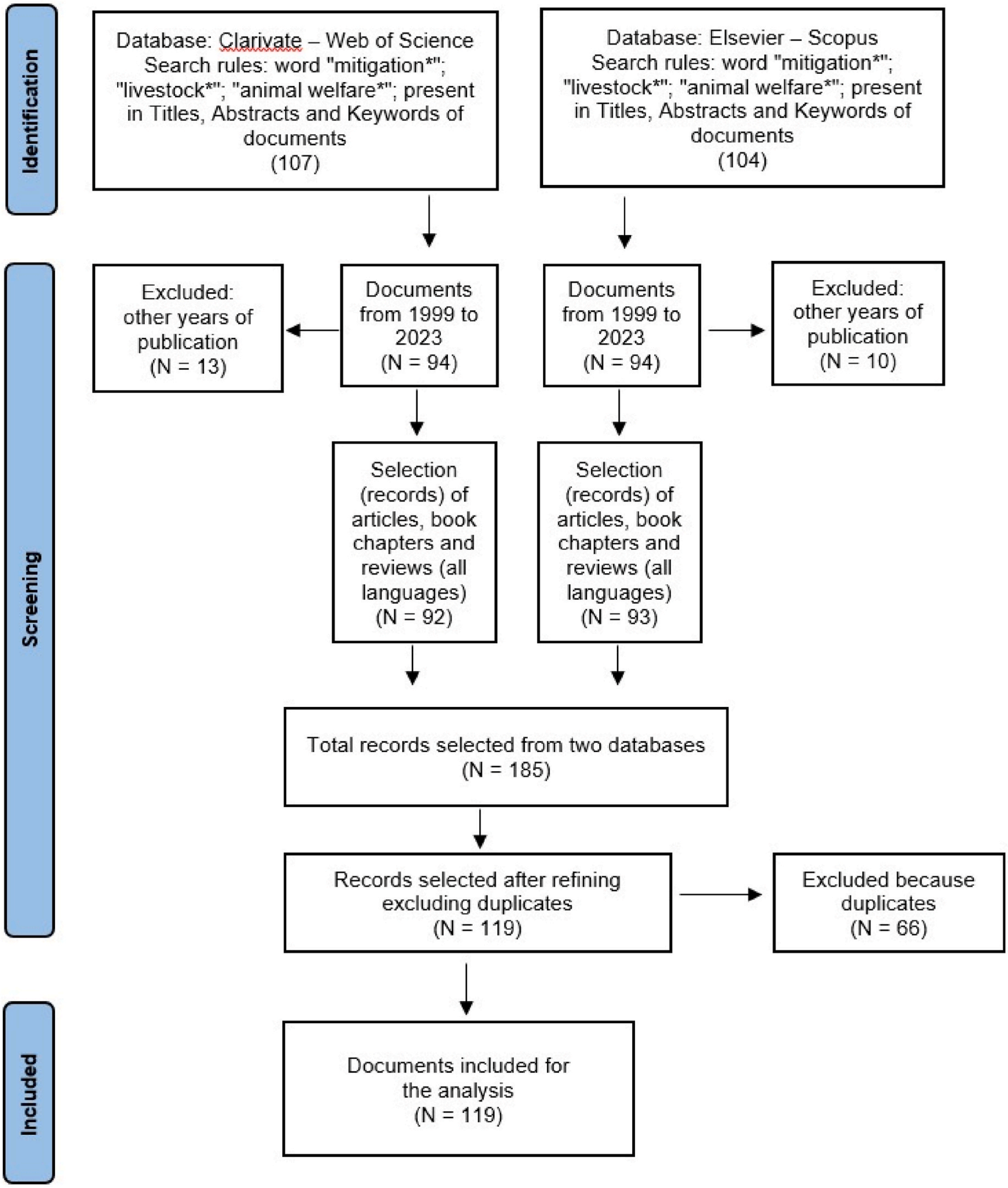

Fig. 1. Inclusion and exclusion criteria using PRISMA protocol.

existing relations among inserted data, like titles, abstracts and keywords for the identification of significant topics within a specific research topic of issue.

3. Overview of global scientific publications

3.1. Descriptive bibliometrics analysis

The data extracted from Scopus and WOS, following the PRISMA protocol, led to carry out some descriptive analyses and specifically to describe the geographical distribution, the total annual distribution of the total number of papers per year, the major Journals in the area of interest.

3.2. Data on publication years

Fig. 2 showed the evolutionary distribution of scientific production in the entire period of activity, i.e. 1999-2023 on the topic selected, “Animal Welfare*“, “Livestock*” and “Mitigation*“.

At the beginning of 2000s, publications on this theme globally were extremely rare; only one paper resulted in 1999 dwelling this thematic, with none in the immediate following here 2000-2003. From 2004 to 2009, there was a steady but minimal output of one article per year. This increased slightly to two publications, followed by four articles in both 2011 and 2012. The period of 2013–2014 saw gradual growth (five articles in 2013 and seven in 2014), after which there was a modest dip to four publications in 2015 and three in 2016–2017. From 2018

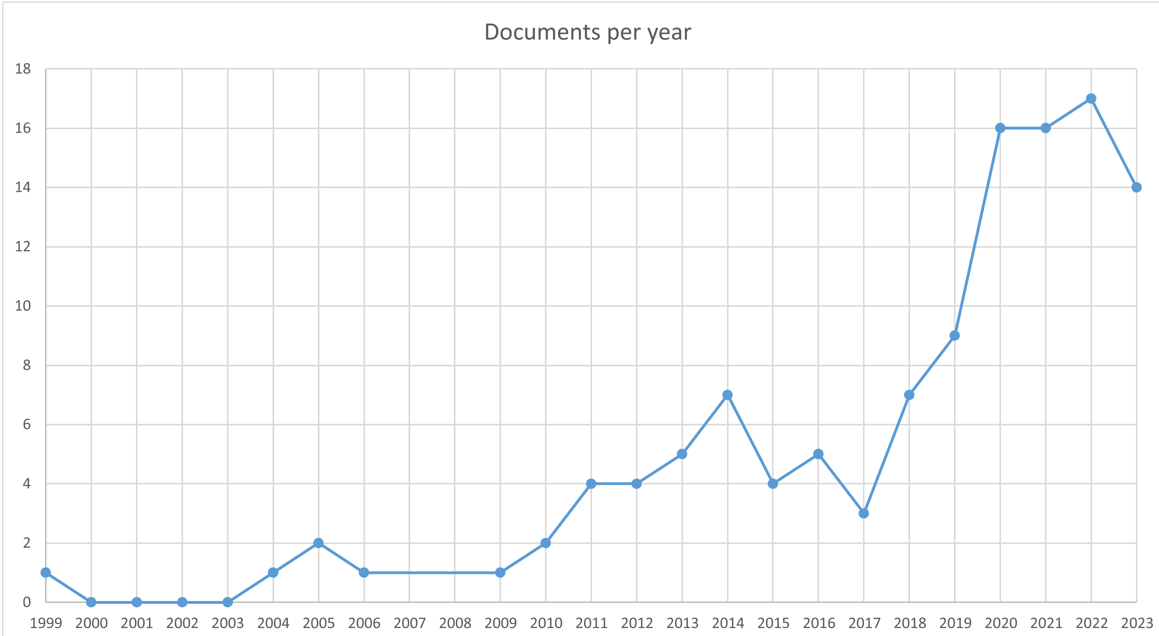

Fig. 2. Evolution of the number of articles published per year
Note: Our elaboration on Scopus and Web of Science Database.

onward, the output resumed an upward trajectory: seven in 2018; nine in 2019. A significant rise to sixteen articles each in 2020 and 2021. From 2021 to 2022 an increasing trend was observed. The apparent decrease in the subsequent year is attributable to incomplete data coverage, as data collection began only in April of that year and does not encompass the full annual period.

3.3. Data on key journals

The crescent trend that identified the latest years as the most productive period revealed the flourishing attention around the "Animal Welfare*", "Livestock*" and "Mitigation*"topic. In particular, Table 1 offers an overview of the articles with the highest citation counts revealing dominant thematic angles within the field, where at the top of the rank, the studies focused on a specific mitigation strategy: Precision Livestock Farming (PLF). Some studies examine how adopting PLF technologies can mitigate environmental impacts by enhancing operational efficiency, animal welfare, and emissions control (Kopler et al., 2023). For instance, Tullo et al. (2019) described PLF as the application of process-engineering tools to automatically monitor, model, and manage livestock production. They emphasized how PLF supports management strategies aimed at reducing greenhouse gas (GHG) and ammonia emissions, as well as nutrient and antibiotic pollution. Subsequent analyses confirm that increased animal efficiency, achieved through PLF, can significantly reduce environmental impact per product unit. Later studies supported these, including Trichkova-Kashamova and Paunova-Hubenova (2023), Marino et al. (2023), and Selvaggi et al. (2024), which further validate PLF's role in environmental mitigation.

Table 1
Rank of first 15 Most-Cited Articles.

Reference	Year	Type	Journal	Cited by
Tullo et al.	2019	Review	Science of the Total Environment	231
Rutherford et al.	2013	Article	Animal welfare	194
Mader et al.	2010	Article	Journal of Animal Science	183
Cleaveland et al.	2006	Article	Veterinary Microbiology	149
Farouk et al.	2014	Article	Meat Science	146
D'Eath et al.	2014	Article	Animal	139
Röös et al.	2018	Review	Agronomy for Sustainable development	134
Lees et al.	2019	Review	Animals	133
Bustamante et al.	2014	Review	Global Change Biology	124
De Boer et al.	2011	Review	Current Opinion in Environmental Sustainability	101
Llonch et al.	2017	Review	Animal	97
Mehrabi et al.	2020	Review	Nature Food	96
Peles et al.	2019	Review	Frontiers in microbiology	75
Thomson et al.	2004	Review	Veterinary Record	58
Johnson et al.	2018	Review	Animal production science	53

Note: Our elaboration with the information extracted from Scopus and Web of Science.

At the second level of the rank, there is a study on the biological factors affecting sow and piglet welfare in relation to large litter size (Rutherford et al., 2013) Research emphasizes the need for integrative approaches combining hereditary selection and perinatal management to mitigate adverse effects.

In the third place (Mader et al., 2010) and similarly the eight (Lees et al., 2019) and the last (Johnson, 2018), the authors address the issue of the heat and cold stress experienced by the animals. Together, these three studies underscore that extreme temperature, whether heat waves or cold snapsare significant stressors for livestock. They highlight both the dynamics of climate change and concerns related to animal welfare, reinforcing the need for adaptive management strategies.

Among the most highly cited articles, four papers examine risks to animal health such as livestock-carnivore conflict (Van der Weyde et al., 2020), microbiological hazard (Farouk et al., 2014), mycotoxicoses causes, i.e. a group of toxic conditions resulting from the ingestion of food contaminated with mycotoxins produced by various saprophytic and phytopathogenic fungi (Peles et al., 2019) and cases of injury (D'Eath et al., 2014; Hall and Fleming, 2021). Another study focuses on vaccination as a mean of disease control (Cleaveland et al., 2006) while a further research addresses disease risk arising from international trade in livestock and livestock products (Thomson et al., 2004).

Röös et al. (2018) propose enhancing productivity in organic farming as an approach to lower environmental burdens per unit of output. In their review referring to Northern European systems, they assess how yield-enhancing measures, such as increased nitrogen inputs, intensified weed and pest control, improved livestock feeding, selective breeding, and loss minimization, affect key sustainability domains, including biodiversity, greenhouse gas emissions, nutrient losses, soil fertility, and animal health and welfare (as well as human nutrition and farm profitability).

Other authors face the topic of greenhouse gas emissions proposing various strategies. Specifically, Bustamante et al. (2014) highlight the potential positive effects of governmental policy interventions in attaining climate change mitigation goals. De Boer et al. (2011) and Llonch et al. (2017) explore options to mitigate greenhouse gas emissions within the animal production chain.

3.4. Geographical distribution of author affiliations

Understanding the geographic distribution of scientific publications can provide valuable insights into where research funding, expertise, and institutional priorities are concentrated. It also underscores the importance of fostering international collaborations to address global challenges more effectively, especially in fields related to environmental and agricultural sciences. Table 2 displays the frequency of papers published across various countries, highlighting the geographic distribution of research within the field. The most represented countries are the United States, United Kingdom, Australia, and Italy. Specifically, the United States accounts for the highest proportion of publications at 46.1%, followed by the United Kingdom with 37.3%, Australia with 32.4%, and Italy at 19.6%. Germany and Canada are tied, each contributing 16.7% of the total publications. Other countries represent less than 15% individually, with Spain recording the lowest percentage at 4.9%.

This distribution reflects a relatively wide geographic spread of research activity, indicating global interest and engagement in the subject. However, it is noteworthy that the majority of the most prolific countries are located in the Northern Hemisphere, with the United Kingdom and Italy as the only two European countries featuring prominently. Their shared continental location may suggest some regional collaboration or focus in research priorities. Conversely, for other continents less represented, significant opportunities arise to increase research efforts in these regions.

3.5. Research area

Fig. 3 illustrates the five primary research domains to which the reviewed papers belong, thereby offering insight into the disciplinary breadth of the literature considered. The results reveal a notable heterogeneity of documents, reflecting a wide spectrum of research interests and approaches. Due to differences in the classification systems used by the two databases analyzed, Scopus and Web of Science, the research fields were consolidated into broader macro-categories to ensure comparability and coherence in the analysis. In particular, the name of the macro-categories was obtained integrating the titles of similar categories.

Table 2
Frequency of papers by review countries.

Countries	Frequency	Countries	Frequency
United States	47	France	10
United Kingdom	38	Netherlands	10
Australia	33	Kenya	9
Italy	20	China	7
Germany	17	Austria	7
Canada	17	India	6
Denmark	12	Brazil	6
New Zealand	12	Nigeria	5
Sweden	10	Spain	5

Note: Our elaboration with the information extracted from Scopus and Web of Science.

The largest identified research field results to be a category so called Agricultural Multidisciplinary, which includes 99 articles and accounts for approximately 34% of the total dataset (289 articles, including potential duplicates). This dominance underscores the central role that agricultural sciences play in the research focus, encompassing topics such as crop production, livestock management, sustainable farming practices, and agro-ecosystem analysis. Following this, the fields of Veterinary Science and Zoology comprise 68 papers, representing around 23% of the total. These areas emphasize animal health, welfare, and behavior, which are critical components of sustainable livestock production and broader ecological studies.

Multidisciplinary Sciences, the third most frequent category with 40 contributions (approximately 14%), reflects studies that integrate multiple scientific perspectives or methodologies, often addressing complex, cross-cutting issues such as climate change impacts, environmental sustainability, and food security. Environmental Science follows closely, with 33 articles (about 11%), highlighting the increasing attention to environmental factors, pollution, resource management, and ecosystem services related to agriculture and animal production. Lastly, Geosciences Multidisciplinary accounts for 30 papers (roughly 10%), indicating research that intersects with earth sciences, including soil science, land use, and climate modeling (Fig. 3).

Overall, the distribution of research areas illustrates the interdisciplinary nature of the field and the necessity of integrating diverse scientific domains to comprehensively address the challenges associated with agriculture, animal health, and environmental sustainability. This broad disciplinary engagement facilitates holistic understanding and supports the development of innovative, evidence-based solutions.

VOSviewer results.

3.6. VOSviewer co-occurrence analysis results

The statistical keyword analysis, conducted using VOSviewer, highlighted the most frequently used terms within the set of 119 articles, revealing the primary research topics studied within the defined search perimeter established by the chosen keyword string (“Animal Welfare*“, “Livestock*“, and “Mitigation*“). This analysis allowed for an in-depth examination of term co-occurrences and relationships, providing valuable insights into thematic clusters and focal points in the literature. Since the data extracted from the Scopus and Web of Science databases employed different coding formats and nomenclatures, it was necessary to harmonize and unify the datasets, converting both datasets into a single RIS file format, then imported into VOSviewer for the co-occurrence map generation. This step ensured consistency and comparability of the keyword data across the two sources, enabling a robust network analysis.

The keyword function in VOSviewer supported the development of the network analysis based on the uniformed dataset, specifically focusing on the TITLE, ABSTRACT, and KEYWORDS fields (TITLE_ABS_KEY), following a systematic workflow as described by Nobanee et al. (2021):

1. Map based on bibliographic data;
2. Type of analysis: co-occurrence;
3. Unit of analysis: keywords;
4. Counting method: full counting;
5. Minimum number of occurrences of a term: 3; (out-put 71 keywords)
6. Number of terms selected: total number of items.

This approach prioritizes the identification of keywords according to their relevance and frequency of co-occurrence, allowing for the visualization of key thematic clusters and the relationships among terms.

VOSviewer software provides two options to develop the keyword co-occurrence: full counting and the fractional counting. The first

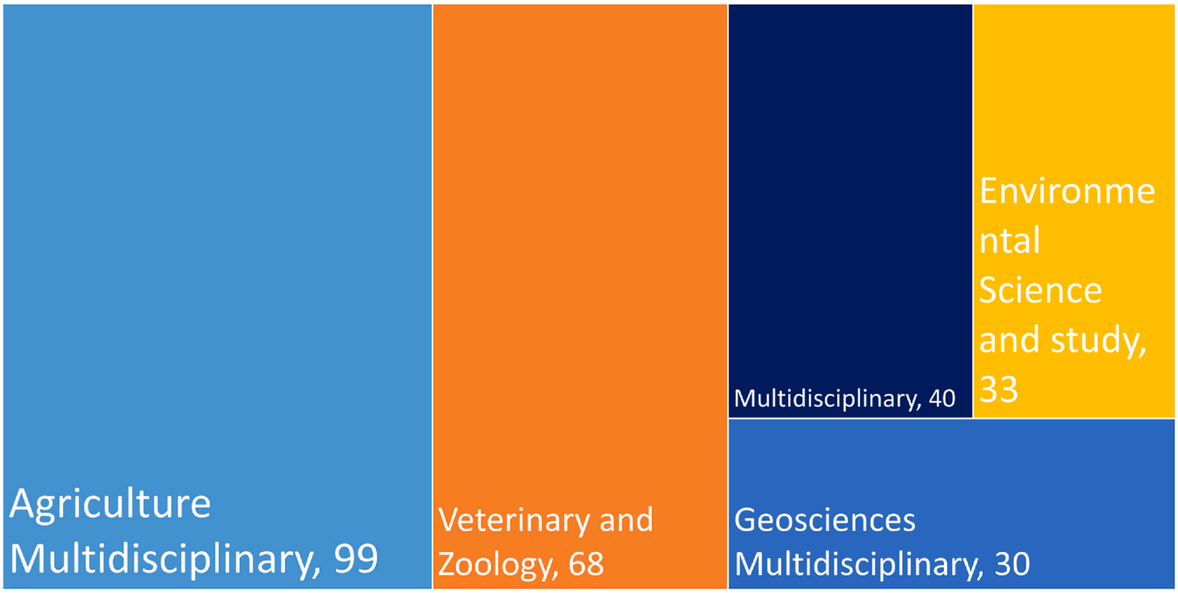

Fig. 3. Research areas on the basis of the number of published articles
Note: Our elaboration on Scopus and Web of Science Database.

feature was adopted for the present analysis for different reasons.

First, VOSviewer gives the option of full counting by default.

Then, following multiple attempts utilizing both available tools for the aggregation and analysis of keywords, the comparative results of the two corresponding network elaborations demonstrated that the full counting method was the most appropriate and informative for the purposes of this study. Specifically, full counting proved to be more effective in emphasizing the total frequency of occurrence of key terms across the dataset. This outcome aligns with previous scholarly findings, which also highlight the advantages of full counting for bibliometric network analyses (Briatore et al., 2026; Van Ninh and Van Tam, 2025). The preference for full counting is largely attributable to its ability to represent the absolute number of keyword occurrences, regardless of the number of authors per document. In contrast, fractional counting adjusts the weight of a keyword based on the number of co-authors, thereby reducing the influence of documents with many contributors. While this approach may offer benefits in certain contexts, such as evaluating individual contributions to collaborative works, it was deemed less suitable for the current study, which aims to explore thematic relevance and frequency across the full body of literature (Perianes-Rodriguez et al., 2016).

Third, the adoption of a broader and more inclusive analytical approach was considered preferable to the more restrictive fractional method, particularly in light of the preliminary screening that had already been performed according to the PRISMA protocol. The PRISMA methodology, widely recognized for its rigor in systematic reviews, had already ensured a high degree of relevance and coherence in the selected corpus of publications. Therefore, applying the additional reduction of keyword occurrence data via fractional counting could have been redundant and potentially detrimental to the comprehensiveness of the analysis. In this context, full counting enabled a richer and more representative mapping of the conceptual landscape.

Fourth, the skimming performed through fractional counting is automatic and algorithm-driven, reducing the number of keywords by approximately 60% without any interpretative input. In contrast, the filtering applied in this study was based on the authors' judgment. This consisted of a minimal intervention, hence, excluding only four keywords (*climate-change*, *ghg emissions*, *animal-welfare*, *environmental impacts*, and *behaviour*) because considered duplicates with lower total link strength compared to their respective counterparts.

Regarding the co-occurrence threshold, the default setting in the system was 5. However, to maintain consistency with the broader approach adopted, this threshold was lowered to 3 in order to include a greater number of terms in the network map.

Initially, the comprehensive search and selection process across the 119 academic papers produced a total of **843 unique keywords**. However, after applying the adjusted threshold of three co-occurrences, the number of keywords retained for inclusion in the final network map was **71**. This refined subset provided a manageable yet representative foundation for the visual mapping of conceptual relationships, balancing analytical clarity with thematic richness.

Once elaborated, the resulting map typically displays a network composed of multiple **nodes**, each of which represents an individual **keyword** extracted from the dataset. The **size of each node** is proportional to the **frequency of occurrence** of the corresponding keyword across the analyzed documents, larger nodes indicate terms that appear more frequently, thus signaling their centrality or relevance within the research field.

3.7. VOSviewer network, cluster and density results

The network map of the present analysis combined a total number of 46 keywords as displayed in Figs. 4 and 5.

The 46 keywords result aggregated into five clusters according to their co-occurrence relationship (Bukar et al., 2023) Fig. 4 highlights the total link strength attributes, which indicate the total strength of one item relative to that of another item, the following considerations had been made.

The density map by items offers the base to develop some observing at the node level. Each colour of the point in the item density visualization indicates the density of items. The system presents a colour range that goes from blue to green and yellow (Van Eck and Waltman, 2014). While the green colour represents the medium colour density, the yellow and the blue represent the extreme, respectively indicating the high weight of the neighbouring items and the small one. The color coding not only enhances interpretability but also assists in identifying which clusters or nodes play a more central or marginal role in the research field under investigation.

The density map presented in Fig. 5 identifies the main topics discussed in the literature, offering a visual representation that closely

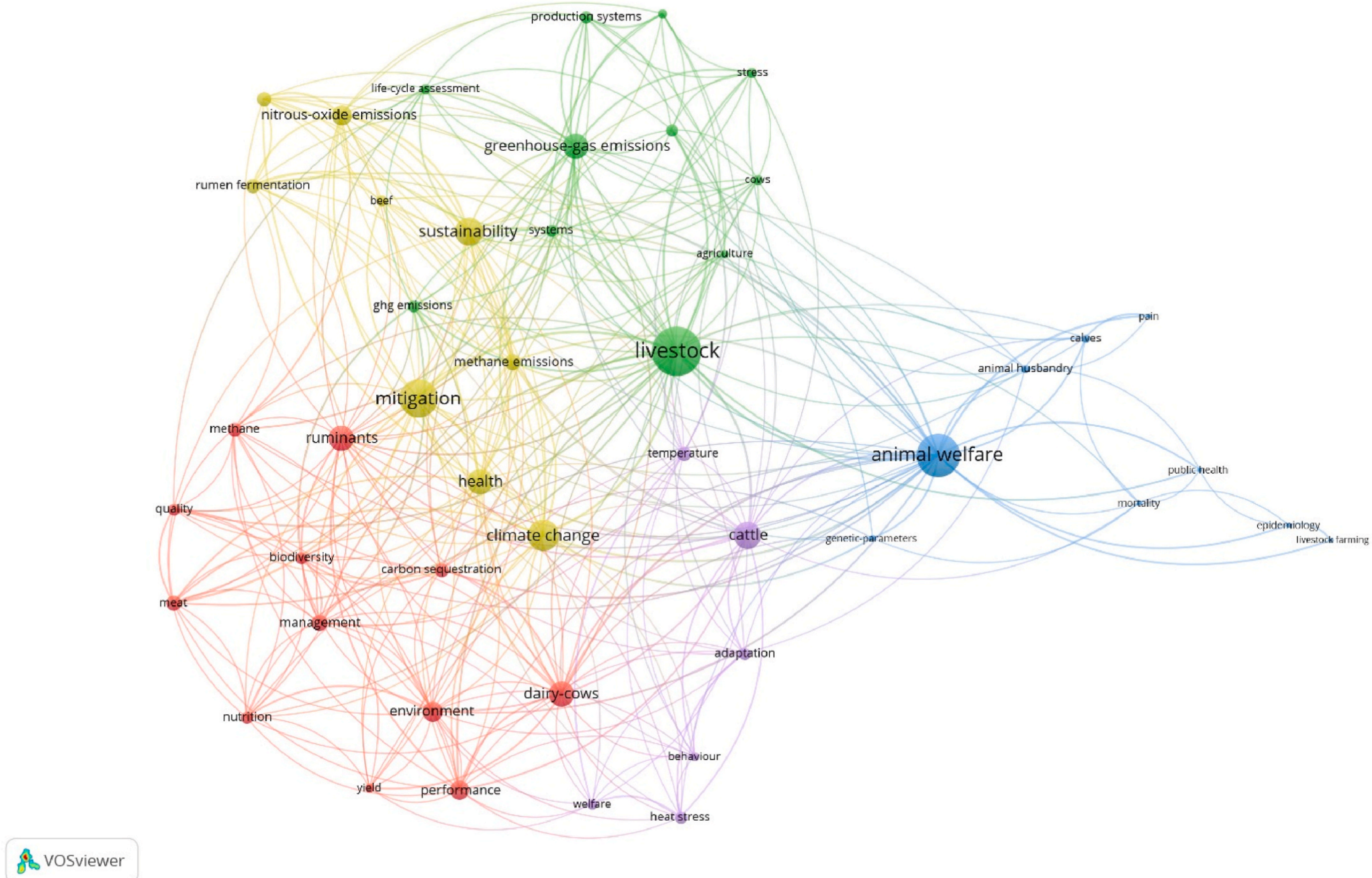

Fig. 4. VOSviewer keywords analysis and co-occurrences in the selected documents.

aligns with the findings derived from the network visualization. In essence, the density map confirms and reinforces the results previously observed, highlighting the same thematic areas and conceptual clusters. This consistency between the two visualizations provides additional support for the robustness and validity of the analysis.

3.8. VOSviewer cluster analysis

Cluster 1, in red, was the most significant with 12 items (see Fig. 6). Its development was around the following topics: Biodiversity, Carbon Sequestration, Dairy Cows, Environment, Management, Meat, Methane, Nutrition, Performance, Quality, Ruminants, Yield.

This aggregation underlines how, in livestock systems, effective management of feed resources and pastures emerges as pivotal for integrate productivity, product quality, animal welfare, and in some case environmental sustainability. Rotational grazing and the use of high-nutritive-value forages enhance ruminant growth, milk yield, and meat quality, while simultaneously promoting soil carbon sequestration (Tullo et al., 2019; Phillips and Heins, 2022). Targeted nutritional choices can improve well-being and reduce environmental impact (McDowell et al., 2022; Hocquette et al., 2014). At the same time, the optimization of diet formulations can reduce methane emissions from enteric fermentation, linking nutritional strategies directly to environmental mitigation benefits (Mader et al., 2010).

Other authors do not underline explicitly the interconnection between animal welfare and environment impact. Pasture management interventions improve performance and reduce emissions (Sturaro et al., 2012; Makkar, 2016**)**. A connection emerged also in the study of Habibullah et al. (2021) where they underline how targeted feeding practices improve milk quality and reduce emissions.

Beyond environmental effects, targeted nutritional interventions improve metabolic health and reduce stress in animals, demonstrating the close interconnection between welfare and productivity (Sievert et al., 2022). Such sustainable management strategies only indirectly suggest that livestock farmers, when implementing feed and pasture practices, have the potential to pursue dual objectives, enhancing animal welfare while mitigating environmental impact.

Cluster 2, in green, was mainly related to the greenhouse gas emissions in livestock management and their measurement. The keywords with the greatest weight were: Agriculture, Ammonia Emissions, Ghg emissions, Global Warming, Greenhouse-gas Emissions, Life-Cycle Assessment, Livestock, Production System, Stress, Systems.

This aggregation suggests how manure management and mitigation of gas emissions suggest another key intersection between welfare and sustainability. Optimized slurry storage, use of dietary additives (Yi et al., 2020), and appropriate barn ventilation decrease ammonia and greenhouse gas emissions, improving respiratory health and reducing stress in housed livestock (Lamkaddam et al., 2021). These practices also contribute to improved animal welfare status (Selvaggi et al., 2024) and to higher productivity by minimizing illness-related inefficiencies (Islam et al., 2021). Appropriate slurry storage and ventilation improve well-being and reduce emissions (Mader et al., 2010); wastewater management strategies reduce emissions by indirectly supporting animal welfare (McDowell et al., 2022).

Life-cycle assessment studies indicate that emission reduction interventions enhance overall system efficiency and resource utilization, therefore, an integrated management of the system reduces stress and GHG (Turner et al., 2022), but there is not explicit referring to animal welfare goal. Manure and emissions management exemplify a practical area where livestock farmers can implement measures that

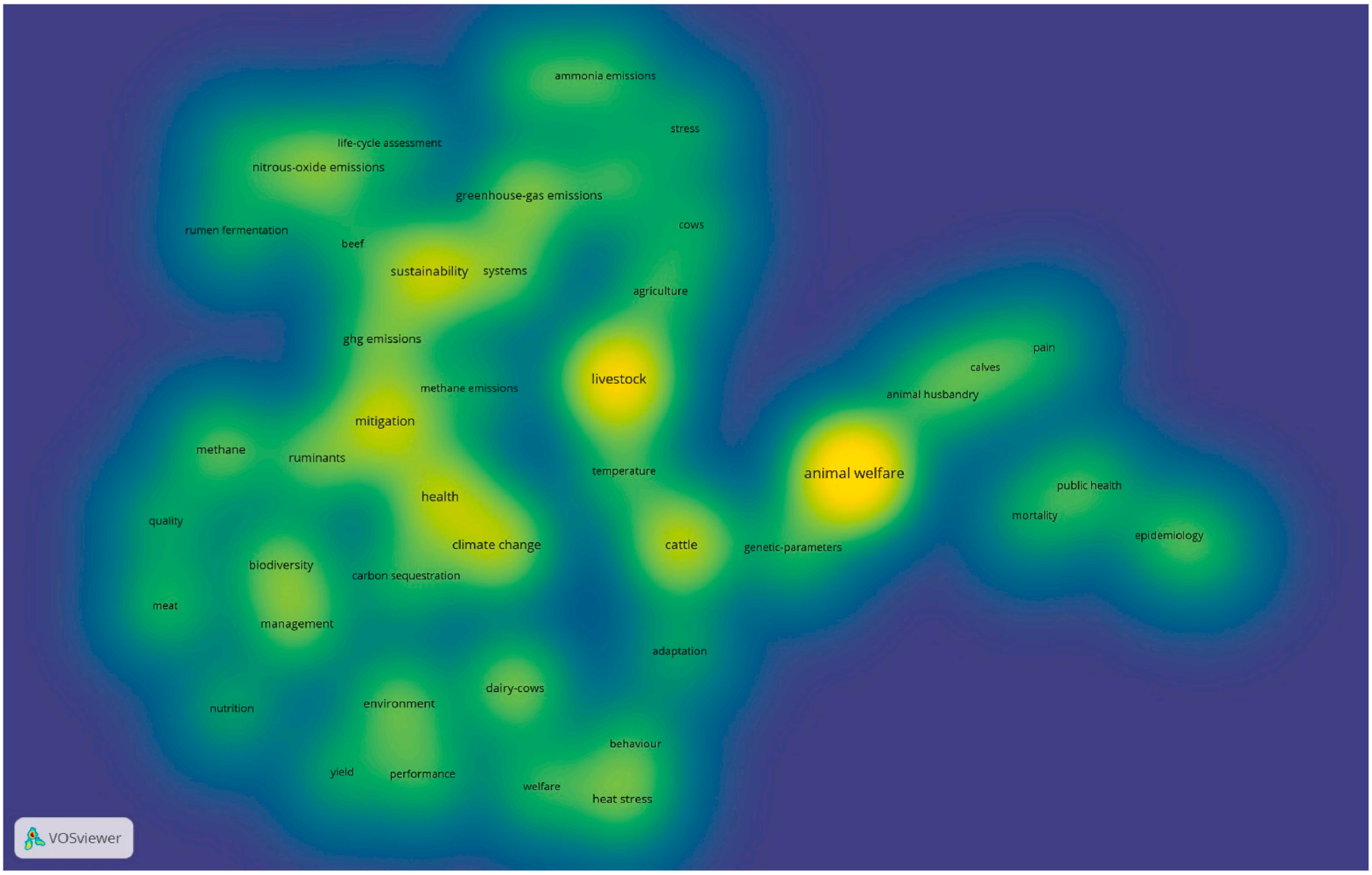

Fig. 5. Density visualization performed by the VOSviewer program.

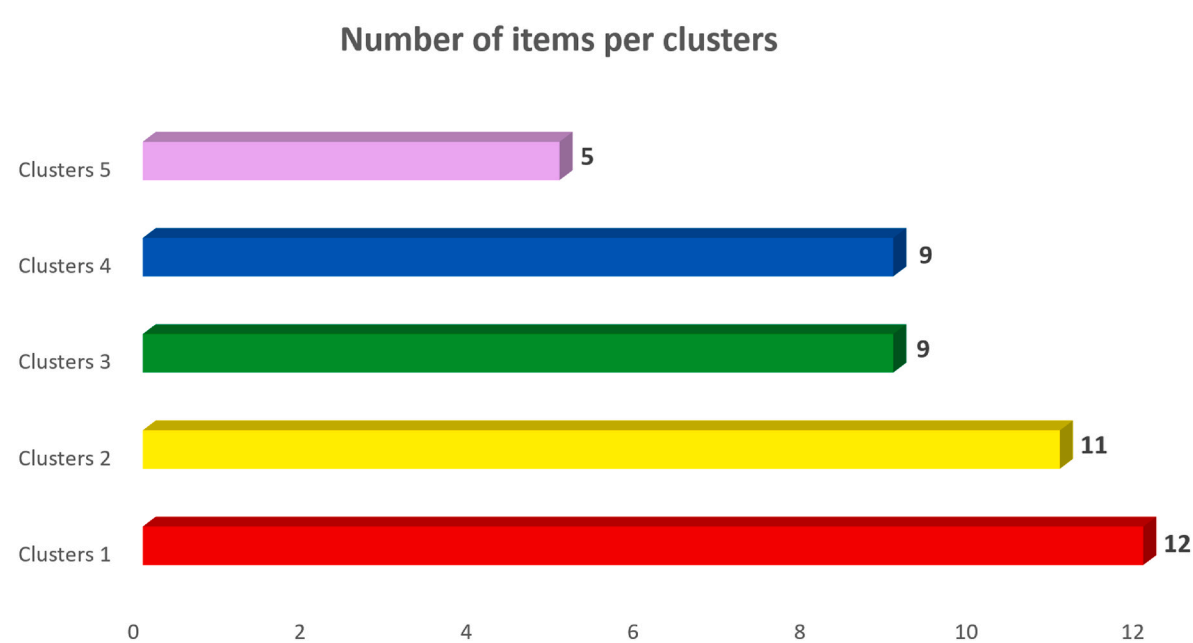

Fig. 6. Cluster analysis

simultaneously promote welfare and environmental goals.

Cluster 3, in blue, showed 9 key terms that focused on safety in various aspects; their management, their treatment as food and risk management aspects. The keywords with the highest weight were: Animal Husbandry, Animal Welfare, Calves, Epidemiology, Genetic-parameters, Livestock Farming, Mortality, Pain, Public Health.

This aggregation is much animal-centered. Animal welfare appears to represent a critical determinant of farm sustainability (Gjerris et al., 2010; De La Cruz et al., 2018; Fernandes et al., 2019), but not in its environmental dimension. Pain management, routine health monitoring, and genetic selection for resilience reduce mortality and disease incidence while enhancing comfort and physiological well-being (Dewell et al., 2014; Lauder et al., 2019; Small et al., 2021). Effective epidemiological surveillance and management of disease risks prevent production inefficiencies and resource wastage, indirectly contributing to lower environmental impact by reducing medical interventions (Whalin et al., 2016; Gilbert et al., 2021). While the reviewed studies focus primarily on welfare outcomes, some evidence suggests that farmers adopting early-life welfare interventions, such as health monitoring and robust genetic lines, may achieve side benefits for sustainability, for example through improved feed efficiency and reduced losses (van Dyke et al., 2021; Johnson et al., 2022). Consistently, other authors have directed their research efforts toward the investigation of animal welfare strategies. (Moggy et al., 2017; O'Connor et al., 2014; O'Connor et al., 2016; Salem et al., 2020). Within this cluster, explicit reporting of integrated strategies that target both welfare and environmental mitigation remains limited. These findings indicate that while animal welfare practices, sometimes focused on pain management, other times on the management of mortality and productivity, can create co-benefits for sustainability, the extent to which livestock farmers consciously implement strategies with dual objectives requires further investigation is not explicit.

Cluster 4, in yellow, aggregated 9 keywords. It delved into consumption, consumer acceptance and willingness to try. The keywords with the most weight were: Beef, Climate Change, Health, Methane Emissions, Mitigation, Nitrous-Oxide Emissions, Rumen Fermentation, Special Topics-Mitigation, Sustainability.

Many authors underline how mitigation strategies for greenhouse gas emissions illustrate the feasibility of concurrently addressing animal welfare and environmental objectives (Shields and Orme-Evans, 2015; Herzog et al., 2018). Indeed, Llonch et al. (2017) develop a direct analysis of GHG reduction strategies from the perspective of animal welfare.

Also, adjustments to rumen fermentation, alternative feeding regimes, and the application of Precision Livestock Farming tools have been shown to reduce methane and nitrous oxide emissions while maintaining productivity and animal well-being. In particular, Tullo et al. (2019) emphasize the optimization of animal well-being through the maintenance of ruminal metabolic and productive performance, aiming to reduce methane emissions while preserving welfare. Trichkova-Kashamova and Paunova-Hubenova (2023) affirm that Precision Livestock Farming's adoption reduce emissions (through feed optimization and targeted management) while ensuring animal welfare by monitoring stress and comfort levels. Also, the implementation of agroforestry practices and sustainable residue management further improves resource efficiency and system resilience by reducing environmental impact, with no reported negative effects on animal health and comfort (Herrero et al., 2023; Galindo-Barboza et al., 2020). Although adoption rate remains low, these technological and managerial interventions provide practical pathways for dual-benefit outcomes. Therefore, the existence of mitigation-focused strategies confirm that livestock farmers can design interventions that meet both environmental and welfare goals, directly addressing the research question on dual-objective management (Goma and Phillips, 2021), highlighting how mitigation and adaptation strategies influence both production performance and animal welfare.

In other authors' studies, the double perspective emerges indirectly. Mehrabi et al. (2020) study the environment, food safety, productivity, and ethical implications, although animal welfare is not always considered directly. Nordgren (2012) expresses concern regarding climate solutions that reduce emissions at the expense of the living conditions of animals.

Cluster 5, in purple, had 5 nodes and it was the smallest. It was mainly about sustainability, innovation and circular economy. The keywords with the highest weight were: Behaviour, Cattle, Heat Stress, Temperature, Welfare.

In this Cluster arise how heat stress represents a major challenge in livestock systems, affecting cattle behavior, physiological welfare, and productivity, with indirect implications for environmental performance (Fuquay, 1981; Herbut et al., 2021; Lees et al., 2019). Behavioral responses such as reduced feeding, increased panting, and altered lying patterns are indicative of thermal discomfort and potential welfare compromise (Lees et al., 2019; Herzog et al., 2021). Targeted management interventions, including the provision of fans, sprinklers, shaded areas, and automated monitoring systems, emerge as interventions to mitigate heat stress, improving both behavioral and physiological indicators of welfare (Johnson, 2018; Islam et al., 2021; Hendricks et al., 2022). The aforementioned authors report strategies to reduce heat stress and improve behavior/physiology, but do not directly link with environmental mitigation.

Moreover, integrating these strategies with environmental management, such as optimized ventilation and feeding schedules, can enhance system efficiency and potentially reduce indirect environmental impacts by maintaining productivity under heat stress conditions (Islam et al., 2021; Herzog et al., 2021; Herbut et al., 2021). Automated and precision monitoring tools allow farmers to adjust environmental and nutritional parameters in real time, thereby aligning welfare optimization with more efficient use of resources (Lees et al., 2019; Johnson, 2018; Hendricks et al., 2022).

While the direct effect of these interventions on greenhouse gas emissions has not been quantified in the reviewed studies, evidence suggests that managing heat stress effectively preserves animal performance, which indirectly contributes to environmental sustainability by reducing inefficiencies and resource wastage (Islam et al., 2021; Herbut et al., 2021).

Also, Morgado et al. (2023) and Mader et al. (2010) when refer to management strategies adopted to preserve animal welfare and productivity under conditions of heat stress, highlighting the importance of combined interventions on nutrition and environmental circumstances. Animal welfare is central, while environmental aspects are not directly measured. An indirect link with environmental sustainability can be glimpsed when they state that a better response of animals to the strategies adopted leads to lower production losses and more efficient use of resources.

Many findings indicate that farmers implement practical management practices that primarily enhance separately animal welfare, and in doing so, may also achieve secondary environmental benefits, partially addressing the research question on dual-objective strategies.

However, Herzog et al. (2021) evaluate cooling systems considering animal comfort and environmental effects. Alleviating heat stress is thus considered to provide dual benefits for animal welfare and emission mitigation, with an additional focus on energy use. The authors explicitly acknowledge that a strategy can improve welfare, but can also increase energy consumption, and therefore must be evaluated as a welfare-mitigation trade-off.

3.9. VOSviewer cluster discussion

3.9.1. Cluster 1

The studies included in this cluster consistently show that feed and pasture management practices are among the most frequently adopted strategies through which livestock farmers can influence both productive efficiency and environmental outcomes. Indeed, Cluster 1 highlights the potential for nutritional and productivity-oriented management to serve as a nexus between animal welfare and environmental sustainability. Optimizing diets for ruminants not only enhances growth, milk production, and overall performance, but also reduces enteric methane emissions, thereby contributing to climate change mitigation.

Rotational grazing systems and the use of high-quality forages contribute to improved soil carbon sequestration and reduced methane emissions per unit of output, particularly when pasture management is optimized (Sievert et al., 2022; Tullo et al., 2019). Nutritional strategies aimed at balancing diets and improving feed efficiency are primarily motivated by productivity and welfare considerations, such as reducing metabolic stress and enhancing rumen function (Mader et al., 2010; Makkar, 2016).

Sturaro et al. (2012) show that certain feeding and pasture management practices can reduce methane emissions and improve feed efficiency while also improving the metabolic health and welfare of ruminants. Habibullah et al. (2021) highlight that: optimized diets and the integration of high-nutritional-value forages can reduce enteric methane emissions without compromising animal welfare.

Importantly, several authors explicitly recognise that environmental benefits often emerge as co-benefits rather than as primary objectives of farmers' management decisions. For instance, McDowell et al. (2022) demonstrate that improved grazing management reduces nutrient losses while supporting animal health, indicating an implicit alignment between welfare-oriented management and environmental mitigation. Similarly, Hocquette et al. (2014) highlight "win–win" strategies in beef systems where quality, efficiency, and welfare improvements coincide with lower environmental impacts. Overall, this cluster suggests that farmers frequently implement feeding and pasture strategies with a strong focus on animal performance and welfare, while environmental mitigation, particularly methane reduction and carbon sequestration, is often an indirect but measurable outcome. Thus, the literature suggests that synergistic objectives are achievable, even if not always explicitly pursued.

3.9.2. Cluster 2

The literature grouped in Cluster 2 demonstrates that livestock farmers often implement emission mitigation practices also to seek animal welfare's care. Manure management strategies and automated monitoring systems housing-based technologies designed to reduce ammonia and greenhouse gas emissions improve indoor air quality, thereby reducing respiratory irritation and stress in livestock (Islam et al., 2021; Lamkaddam et al., 2021; Yi et al., 2020). Such measures, though environmentally driven, indirectly also create conditions that enhance animal comfort and health. Environmental control within barns, including optimized ventilation and climate management, alleviates thermal and physiological stress while contributing to emission reductions at the system level (Mader et al., 2010; Selvaggi et al., 2024). From a system perspective, life-cycle assessments indicate that interventions reducing nutrient losses and emissions can enhance production efficiency without negatively affecting animal well-being (Turner et al., 2022). Overall, the evidence in Cluster 2 highlights that livestock farmers can adopt practices that reduce environmental impact while preserving animal welfare, although welfare improvements are often co-benefits rather than explicitly targeted objectives. This underscores the need for more intentional dual-objective strategies to fully address the goal to enhance the level of sustainability in a proportional way among its different dimensions and in particular the environmental and the ethic one.

3.9.3. Cluster 3

Cluster 3 highlights the strong focus of livestock management research on animal outcomes, particularly caring for welfare in young stock, disease prevention, and genetic selection. Several authors argue that improving welfare is a critical determinant of long-term environmental and production outcomes (Gjerris et al., 2010; De La Cruz et al., 2018; Fernandes et al., 2019). The integration of animal welfare considerations with mitigation strategies emerges as a synergistic approach. Indeed, on one hand empirical studies show that interventions such as pain management, routine health monitoring, and breeding for resilience improve mortality rates, reduce disease incidence, and enhance physiological well-being (Dewell et al., 2014; Lauder et al., 2019; Small et al., 2021). On the other hand, these strategies primarily target welfare objectives, they can generate indirect environmental benefits by minimizing resource waste, such as feed and medical inputs, through more efficient and healthier livestock production (Whalin et al., 2016; Gilbert et al., 2021). Early-life welfare interventions, including monitoring and selection of robust genetic lines, have been associated with improved productivity and feed efficiency, potentially contributing to reduced environmental pressure (van Dyke et al., 2021; Johnson et al., 2022). However, much of the research within this cluster (Salem et al., 2020; Moggy et al., 2017; O'Connor et al., 2014, 2016), emphasizes welfare outcomes without explicitly assessing farmers' adoption of practices designed to achieve simultaneous environmental mitigation. Overall, the evidence suggests that while animal welfare interventions may create co-benefits for sustainability, but indirectly. In fact, environmental mitigation is not an explicit objective of the welfare strategies discussed. The extent to which livestock farmers intentionally implement strategies with a dual focus on both welfare and environmental impact remains unclear, highlighting a significant knowledge gap in the practical integration of these objectives. Therefore, it emerges an important asymmetry in the literature, indicating that welfare-driven management does not necessarily translate into explicit environmental action, partially limiting its contribution to the research question.

3.9.4. Cluster 4

The studies included in Cluster 4 most explicitly address the relationship between environmental mitigation and animal welfare. Several studies explicitly link environmental and welfare objectives, suggesting that carefully designed interventions can achieve dual benefits (Shields and Orme-Evans, 2015; Herzog et al., 2018). Interventions targeting rumen fermentation, alternative diets, and precision feeding are shown to reduce methane and nitrous oxide emissions while maintaining or improving animal health and productivity (Llonch et al., 2017; Tullo et al., 2019). Precision Livestock Farming (PLF) technologies provide concrete tools for management strategies explicitly designed to balance all the sustainability dimensions through a holistic perspectice embracing productivity, welfare, and environmental performance (De Mel et al., 2023).

Moreover, broader system-level interventions, such as agroforestry and sustainable residue management, further enhance resilience and reduce environmental impacts without compromising animal well-being (Herrero et al., 2023). Nevertheless, adoption remains uneven, often constrained by economic and structural barriers. Goma and Phillips (2021) emphasize that while technological solutions can deliver dual benefits, their effectiveness depends on context-specific implementation. Overall, this cluster offers the strongest evidence in support of the research question, demonstrating that livestock farmers can implement practices explicitly designed to achieve both welfare enhancement and environmental mitigation, although widespread uptake remains limited.

3.9.5. Cluster 5

In the Cluster 5 emerges that heat stress management practices are widely adopted to protect animal welfare under rising temperature conditions (Herbut et al., 2021; Lees et al., 2019) with environmental considerations addressed unevenly. Overall, the authors of this subgroup address heat stress mainly as a well-being and performance problem, while the reduction of environmental impact emerges only as an indirect consequence of greater production and management efficiency. This indicates that, in Cluster 5, farmers implement animal welfare-targeted practices that can contribute to environmental sustainability, but rarely adopt such strategies with the explicit intention of pursuing the two objectives simultaneously, thus providing a partial but informative answer to the research question.

For instance, cooling systems, shading, and automated monitoring can improve feed efficiency and reduce emissions intensity per unit of output, environmental mitigation is rarely framed as a primary objective. Precision Livestock Farming tools enhance early detection and adaptive management, supporting welfare while potentially improving resource efficiency (Johnson, 2018; Islam et al., 2021). However, only a limited number of studies explicitly evaluate the environmental costs of these interventions. Herzog et al. (2021) stand out by quantifying energy use alongside welfare gains, directly addressing the welfare-mitigation trade-off. More broadly, climate adaptation strategies are rarely framed as emission mitigation tools, even though welfare protection under heat stress can prevent productivity losses that increase emissions intensity (Morgado et al., 2023; Mader et al., 2010).

Consequently, this cluster indicates that farmers actively implement welfare-oriented strategies that may indirectly influence environmental performance, but explicit integration of mitigation goals remains limited. This cluster therefore suggests that explicit dual-objective framing is still the exception rather than the norm, revealing a need for more integrated environmental assessments.

Overall, the authors of this subgroup address heat stress mainly as a well-being and performance problem, while the reduction of environmental impact emerges only as an indirect consequence of greater production and management efficiency. This indicates that, in Cluster 5, farmers implement animal welfare-targeted practices that can contribute to environmental sustainability, but rarely adopt such strategies with the explicit intention of simultaneously pursuing the two objectives, which underlie the research question of the present study.

3.10. VOSviewer high-frequency keywords analysis

Table 3 shows some results related to the co-occurrence and the total link strength approaches. These two analyses differ in scope and interpretation. In fact, the first quantifies the number of documents in which a keyword occurs encompassing all 46 items. Specifically, the occurrences attribute reveals the number of documents containing a given keyword; when using the full counting, it specifies the total number of times a term appears across all documents (Van Eck and Waltman, 2014). Instead, the total link strength one reveal the weight of a keyword, but only within the context of the cluster to which it belongs. Moreover, the total link strength attributes indicate the overall strength of connection among items. These linkages thus enable further interpretation and discussion.

The keywords with the highest weight and occurrence levels were *animal welfare*, *livestock*, and *mitigation*, reflecting their central importance in driving the present research.

Referring to the occurrence attribute, *cattle* and *sustainability* appear alongside *mitigation*, each with the same score of (9). This result is unsurprising, as sustainability, as a broader concept, aims to support both mitigation efforts and animal welfare practices, consistent with its environmental and ethical dimensions. *Climate change* appears immediately below, as it indeed represents one of the outcomes resulting from the adoption of various activities, which again fall under the broader concept of sustainability. *Cattle*, on the other hand, signify the animal at the center of all management practices related to mitigation and animal welfare discussed here.

With regard to total link strength, *climate* shows a higher weight than both *cattle* and *sustainability*. This finding does not result unexpected, as occurrences reflect the frequency of interaction among items, while total link strength captures their absolute weight which, in the context of our analysis, is notably high for *climate*.

To strengthen the analysis, a more in-depth examination.

Table 3
Rank of first 15 most keywords' occurrences and links' strength.

Keyword	Occurrences	Total link strength
animal welfare	19	59
livestock	14	63
mitigation	9	51
cattle	9	36
sustainability	9	35
climate change	8	40
health	8	33
dairy-cows	6	32
greenhouse-gas-emissions	6	32
nitrous-oxide emissions	6	26
ruminants	6	32
environment	5	25
management	5	22
methane	5	18
biodiversity	5	16
heat stress	5	16
systems	5	16

Note: Our elaboration with the information extracted from Scopus and Web of Science.

4. VOSviewer high-frequency keywords discussions

4.1. Animal welfare

Widespread concerns regarding animal welfare and environmental sustainability have contributed to a growing awareness of the urgent need for adaptation within animal production systems. These concerns have been intensified in recent years due to increasing public scrutiny, evolving consumer expectations, and the global drive to mitigate the effects of climate change. However, accordingly to some authors (Shields and Orme-Evans, 2015), efforts to reduce greenhouse gas (GHG) emissions in the context of animal agriculture have not always adequately accounted for animal welfare considerations. Many of the proposed mitigation strategies, although environmentally oriented, may not be socially or ethically sustainable, particularly when they compromise the well-being of animals.

This section aims to identify the main emission abatement strategies discussed in the climate change literature that have the potential to negatively impact animal welfare, while also providing a detailed examination of the specific challenges and trade-offs involved. Indeed, environmental pressures such as those arising from temperature extremes, altered housing systems, or feed modifications can have direct and indirect effects on animal behaviour, growth, development, and overall welfare.

Understanding these complex interactions is crucial for developing integrated solutions that balance environmental objectives with ethical and welfare standards in livestock production.

4.2. Mitigation

The keyword "mitigation" emerged in the literature as a multifaceted concept, encompassing various dimensions that extend beyond its conventional environmental meaning. First and foremost, mitigation refers to practices aimed at addressing environmental challenges, such as the reduction of greenhouse gas emissions and other negative ecological impacts. Simultaneously, the term also includes strategies focused on alleviating animal suffering and pain, thus contributing to an overall improvement in animal welfare (van Dyke et al., 2021; O'Connor et al., 2014; Cardoso et al., 2016; Whalin et al., 2016; Moggy et al., 2017; Lauder et al., 2019; Sheil et al., 2020). In this context, mitigation efforts are closely tied to enhancing the general welfare status of animals, as also noted by Cleaveland et al. (2006). Moreover, the concept of mitigation also extends to the economic sphere, particularly in efforts to minimize financial losses associated with the spread of animal diseases, such as rabies and other zoonotic infections. These diseases not only affect livestock and wildlife populations (Mello et al., 2019; Hasler and Howe, 2012; Nogueira et al., 2011), but also pose significant threats to human health, thereby generating a range of socio-economic repercussions (Adebowale et al., 2020; Carpenter and Rich, 2012; Peles et al., 2019; Zheng et al., 2013). This dual impact reinforces the importance of integrated, cross-sectoral mitigation strategies. Additionally, it has been demonstrated that pain and discomfort in farm animals can lead to reduced production efficiency and growth rates, which in turn can have cascading effects on both animal health and farm profitability (Salem et al., 2020). In this regard, the adoption of organic agricultural methods has been identified as a promising approach that simultaneously supports animal welfare goals and contributes to broader environmental sustainability objectives (Röös et al., 2018).

4.3. Health

Efforts aimed at mitigating environmental impacts can yield substantial benefits for both animal and human health. Within this integrated framework, health improvement emerges as a proactive strategy capable of simultaneously advancing animal welfare and achieving environmental sustainability goals (Llonch et al., 2017). This dual benefit reinforces the importance of adopting holistic approaches that consider the interconnectedness of ecological, animal, and human systems.

In alignment with this perspective, the keyword “health” tends, as it appears in the analyzed literature, to encompass both dimensions: the well-being of animals and the health of humans (Arnould et al., 2013; Gilbert et al., 2021). This dual use reflects a growing recognition within the scientific community of the One Health approach, which emphasizes the interdependence of all living systems.

Among the strategies identified to support this goal, one of the most discussed is the reduction of meat consumption (Lusk et al., 2022). By decreasing demand for livestock production, this shift can help lower greenhouse gas emissions, reduce environmental degradation, and limit the pressure on animal systems, ultimately contributing to both human and animal health outcomes.

However, such a transformation would require significant changes in individual lifestyles and dietary habits, which are far from straightforward. These changes often stem from ethical considerations and may reflect deeper value-based commitments to the principles of animal welfare and environmental responsibility (Thomson et al., 2004; Farouk et al., 2014). As such, the act of reducing meat consumption can also be viewed as a moral and cultural expression of a broader respect for animal life and ecological balance.

To promote and strengthen this type of integrated approach, several authors have emphasized the importance of policy interventions aimed at increasing public awareness and encouraging a shift toward ethical and sustainable consumption models (Sievert et al., 2022). From this perspective, raising awareness is not only a matter of information dissemination, but also a strategic tool to foster socially responsible behavior and to align consumer practices with broader environmental and animal welfare goals.

Empirical studies have demonstrated that a significant segment of consumers is willing to pay a premium price for sustainably produced meat products, thereby providing a market-driven incentive for producers to adopt more sustainable livestock systems (Charry et al., 2019; Phillips and Heins, 2022; Engelke, 2009). This willingness-to-pay reflects a growing consumer consciousness regarding the ethical and environmental implications of food choices and can serve as a lever for change in agricultural production models.

In parallel, other scholars have emphasized the urgent need for public policies that regulate agricultural practices and provide clear regulatory frameworks aimed at reducing greenhouse gas (GHG) emissions (Chen and Di Lernia, 2022; Bustamante et al., 2014; Quander-Stoll et al., 2020; Mehrabi et al., 2020). These policy interventions are considered essential for driving systemic change and ensuring that mitigation efforts are effective, scalable, and equitable. Ultimately, such measures are intended not only to reduce environmental impact, but also to safeguard both animal and human health, thereby reinforcing the interconnected nature of sustainability, public health, and ethical food systems.

In addition, implementing nutritionally balanced and health-oriented dietary programs for livestock not only reflects a commitment to animal well-being, but also contributes meaningfully to the reduction of environmental impact (Llonch et al., 2017). Properly formulated diets represent a best practice that supports the physiological health of animals while also aligning with broader sustainability objectives.

One of the key environmental benefits associated with optimized animal nutrition is the potential to reduce enteric methane emissions, a major source of greenhouse gases in livestock systems. As highlighted by De Boer et al. (2011), improving feed composition can significantly lower enteric gas production, thus mitigating the overall pollution burden linked to animal agriculture. This reduction not only benefits the environment but also has positive implications for both human and animal health, given the strong interrelation between ecosystem integrity and public health outcomes (Racciatti et al., 2023).

A particularly promising and sustainable strategy involves the use of alternative feed resources derived from agroforestry plants. As proposed by Salem et al. (2020), integrating such feed sources can help diversify animal diets, reduce dependency on conventional and often resource-intensive feed crops, and promote circular agricultural systems. These innovative practices exemplify virtuous models that balance productivity, animal welfare, and environmental preservation.

4.4. Ruminants

Some authors have raised specific health concerns regarding ruminants, highlighting their significant contribution to greenhouse gas emissions (Mlambo and Mnisi, 2019; Torres et al., 2020), which in turn negatively affect the environment (McDowell et al., 2022). In response to these concerns, one proposed approach involves utilizing local feed resources grown on-farm, and integrating grazing techniques that combine crop and livestock production within a single agricultural system (Van Der Linden et al., 2015). Firstly, natural feeding practices are considered more respectful of animal welfare, as they avoid the use of non-organically certified feed additives and promote a healthier diet for the animals (Escribano, 2018). The type of feed influences not only the nutritional status of the animals but also the quantity and quality of their excretions, which directly impacts environmental outcomes (Galindo-Barboza et al., 2020). Furthermore, maintaining clean management of dunging areas contributes to reducing emissions and environmental contamination (De Boer et al., 2011; Dick et al., 2021). Secondly, on-farm feed production reduces the reliance on imported feed and decreases the need for long-distance transportation, thereby lowering the carbon footprint and overall greenhouse gas emissions associated with livestock production. Thirdly, these factors also lead to economic savings and support the implementation of a circular economy model, enhancing both economic viability and environmental sustainability. Another promising approach is the use of hybrid feeding systems, which combine grazed dairy systems with confined feeding operations. This hybrid model allows for controlled dietary intake, which can help mitigate animal welfare issues related to climatic extremes by optimizing nutrition under varying environmental conditions.

4.5. Cattle

The prominence of cattle as a keyword in the literature is unsurprising, given its central role within livestock systems and its significant environmental impact. Several authors have highlighted that rumen fermentation in cattle is one of the largest contributors to pollution within agricultural activities, primarily due to the emission of methane, a potent greenhouse gas (Sturaro et al., 2012). Among the mitigation strategies explored specifically for cattle, Chará et al. (2019) underline that the use of *Leucaena leucocephala* represents a promising approach to promote sustainable ranching. This forage species has been demonstrated to function as an effective climate change mitigation measure, contributing to enhanced carbon sequestration both above and below ground, while simultaneously reducing methane emissions from ruminant digestion. Importantly, the integration of *Leucaena leucocephala* into cattle feeding systems also aligns with animal welfare objectives, providing nutritious fodder that supports animal health and productivity. Beyond its direct effects on emissions and animal welfare, this solution addresses the imperative of biodiversity conservation, as the vegetative characteristics of Leucaena contribute to increased habitat complexity, thereby fostering a more resilient and ecologically diverse agroecosystem (Chará et al., 2019).

4.6. Greenhouse-gas-emissions

The adoption of pastoral systems result to be significant contributors to greenhouse gas (GHG) emissions (Peri et al., 2024; Nwobodo et al., 2022). A proposed strategy in the literature to reduce their environmental impact involves the intensification of ecological processes within these systems (Hara et al., 2022; Sánchez and Montero, 2023). This approach aims simultaneously to achieve economic, environmental, and social sustainability, fostering a more balanced and resilient agricultural framework (Thaxton et al., 2016; Ramirez et al., 2021; Galioto et al., 2017). Promoting longer rumination times is identified as a best practice for mitigating methane emissions, as it effectively reduces methane production during digestion and in milk production systems. (Bačėninaitė et al., 2022). However, such mitigation methods are not widely applied in extensive grazing systems. Therefore, some authors suggest implementing these strategies over extended periods and across large animal populations, with particular attention to rumination duration as a key indicator of optimal ruminal fermentation and overall physiological state. In addition, nutritional innovations emerge as essential within behavioral management context. Recent studies emphasize the potential of developing natural chemical compounds through improved nutritional management specifically to reduce methane production in the rumen (Bačėninaitė et al., 2022). Continuous monitoring of gas concentrations is critical for assessing air quality and guiding the adoption of both direct and indirect mitigation approaches (Herrero et al., 2023). This monitoring not only supports environmental goals but also contributes to animal welfare by ensuring healthier air conditions within livestock facilities (D'Urso et al., 2023). Technologies focused on air pollutant treatment and improvements in air recirculation systems have shown promise in effectively mitigating the environmental impact of livestock operations (Yi et al., 2020). Furthermore, the development of more reliable measurement methods for gas concentrations in open and semi-open dairy housing systems is urgently needed, as current research in this area remains limited (D'Urso et al., 2023). Alongside methane, efforts to mitigate other gases such as nitrous oxide are also critical. Many authors explore various technologies functionalities and procedures outputs in order to address nitrous oxide emissions, with ongoing work to validate effective management strategies (Lamkaddam et al., 2021; Milne, 2005; Christ and Benz, 2020). For example, targeted treatments involving adjustments of airflow rates have been tested, demonstrating significant mitigation potential for reducing these emissions (Tullo et al., 2019; Christ and Benz, 2020; Menardo et al., 2021).

4.7. Sustainability

The concept of sustainability represents a holistic framework that integrates a wide range of objectives, including environmental mitigation, animal welfare, economic viability, and social responsibility. More recently, another dimension has emerged that broadens the analysis in this type of perspective, namely, governance. Consequently, sustainability is frequently cited in the scientific literature as a foundational driver for innovation and policy development within the agricultural sector (Sturaro et al., 2012; Llonch et al., 2017; Galioto et al., 2017; Escribano, 2018; Hara et al., 2022) where the sustainability transcends singular goals by advocating for a balanced approach that ensures the long-term resilience of livestock production systems.

In the context of this review, relevant studies have articulated two main perspectives that capture the complexity of applying sustainability principles in livestock management. The first perspective emphasizes the value of integrative approaches that align economic, environmental, and social goals. These approaches are grounded in the understanding that sustainable farming systems must not only reduce greenhouse gas emissions and protect animal welfare but also maintain profitability and support rural livelihoods. Empirical evidence supports this view, with research demonstrating that farms exhibiting the highest economic efficiency also tend to have the lowest environmental footprints. For example, Hocquette et al. (2014) and Turner et al. (2022) found that efficient resource use and optimized production practices could simultaneously reduce environmental impacts such as methane emissions and land degradation, without compromising productivity.

However, the second perspective presents a more cautious or critical stance, recognizing that the path to sustainability is fraught with tradeoffs and challenges. Some studies report that, despite the promise of sustainability interventions, the net benefits achieved are often less significant than anticipated. Moreover, these interventions can sometimes result in increased animal welfare costs that exceed socially acceptable limits (Ben-Ami et al., 2014). This suggests that certain mitigation strategies, while beneficial for environmental outcomes, may impose stress or hardship on animals if not specifically designed and implemented. Such findings highlight the need for a nuanced evaluation of sustainability measures, ensuring that improvements in one domain do not inadvertently cause harm in another.

This dual perspective underscores the complexity of achieving true sustainability in livestock systems. It calls for multidisciplinary research and stakeholder collaboration to develop and adopt practices that are economically viable, environmentally sound, and ethically responsible. Furthermore, it stresses the importance of adaptive management, where continuous monitoring and feedback allow for the refinement of strategies to better meet diverse and sometimes competing objectives.

In conclusion, while sustainability remains a compelling and essential goal in contemporary livestock production, it requires a careful balancing act. Recognizing the interconnectedness of ecological, economic, and social factors is crucial to developing innovative and practical solutions that can foster resilient and responsible agricultural systems for its future sustainable development.

4.8. Heat stress and behavior

Unsurprisingly, heat stress emerges as a prominent keyword within the literature on livestock welfare and environmental impacts (Luo et al., 2022). Its significance parallels that of animal behavior, given that heat stress is a persistent and influential factor shaping behavioral responses in animals (Johnson, 2018; Goma and Phillips, 2021; Islam et al., 2021). This close connection underscores the critical relationship between heat stress and overall animal welfare (De La Cruz et al., 2018; Hendricks et al., 2022).

Several authors have emphasized the direct causal links between climate change impacts and the prevalence of heat stress, highlighting how adverse weather conditions detrimentally affect livestock performance, including growth, reproduction, and health (Dean et al., 2023). To better understand and mitigate these effects, the concept of heat stress zone mapping has been proposed, utilizing a specialized environmental indicator known as the Temperature-Humidity Index (THI). This index allows researchers and practitioners to quantify thermal stress in livestock environments and formulate tailored recommendations aimed at improving the thermal conditions experienced by animals, thereby enhancing welfare outcomes (Adjassin et al., 2020).

Building on this approach, Mader et al. (2010) introduced a more comprehensive climate index that integrates humidity and wind speed alongside temperature, providing a multidimensional assessment of environmental factors relevant to animal welfare objectives. Such indices are critical tools in designing management practices and infrastructure that mitigate heat stress impacts.

At a more fundamental level, investigations into the molecular and genetic mechanisms underlying the heat stress response have revealed promising pathways for mitigation. Specifically, quantitative trait loci

(QTL) mapping linked to three physiological indicators of heat stress has demonstrated that these traits are heritable. This discovery highlights the potential for genetic selection strategies to breed animals more resilient to heat stress, contributing to sustainable adaptation to changing climates (Rutherford et al., 2013). Furthermore, animal translocation emerges as a mitigation strategy, particularly for wildlife populations in development-affected areas, aiming to reduce exposure to heat stress and its associated negative impacts (Villaseñor et al., 2013).

Collectively, these findings confirm a complex and interdependent relationship among environmental factors inducing heat stress, animal behavior, welfare status (De La Cruz et al., 2018), and even meat quality parameters (Chauhan et al., 2023). This nexus has profound implications for livestock production systems. In particular, rising temperatures driven by climate change pose a threat to ruminant production capacity, as heat stress can limit feed intake, growth rates, and reproductive efficiency (Goma and Phillips, 2021).

The consequences extend beyond welfare to encompass broader economic considerations, as environmental fluctuations affecting animal behavior and health ultimately influence farm productivity and profitability (Morgado et al., 2023). Therefore, addressing heat stress is critical not only for ethical reasons but also for the sustainability and economic viability of animal agriculture.

While heat stress has been a focal point, it is important to acknowledge that cold stress also presents significant challenges, especially as climate change leads to increased temperature variability and extreme weather events (Nielsen et al., 2020). Comprehensive mitigation strategies must therefore account for the full spectrum of thermal stressors affecting livestock.

Lastly, some authors have proposed depopulation, the strategic reduction of animal numbers, as a mitigation measure designed to balance animal welfare concerns with environmental sustainability objectives (Baysinger et al., 2021). While this approach remains controversial, it underscores the complex trade-offs involved in managing livestock systems under the pressures of a changing climate.

4.9. Biodiversity

This term emerges as a key concept, which is not unexpected, given that within environmental stewardship and associated mitigation strategies it constitutes a fundamental element to be preserved. Biodiversity, indeed, is a critical concept in environmental conservation, serving as a cornerstone for the development and implementation of effective mitigation strategies. Its preservation is essential for maintaining ecosystem resilience, supporting agricultural productivity, and sustaining animal welfare. Nonetheless, modern agricultural practices frequently contribute to biodiversity decline. These practices include overexploitation of land resources, intensive tillage, drainage of wetlands, monoculture crop rotation, overgrazing, and the widespread application of chemical pesticides and fertilizers (McLaughlin and Mineau, 1995; Phillips and Heins, 2022). Such activities disrupt soil structure, reduce habitat heterogeneity, and adversely affect the abundance and diversity of native species.

In addition to anthropogenic pressures, several natural and anthropogenic factors exacerbate biodiversity loss, including habitat degradation and fragmentation, the introduction and spread of invasive alien species, pollution, and climate change-related shifts in environmental conditions (Lunney, 2011; Thomson et al., 2013; Hynek et al., 2005). These stressors collectively undermine ecosystem services that are vital for sustainable agriculture and livestock production.

In response to these challenges, recent research has explored innovative approaches to mitigate the environmental footprint of animal housing. For instance, the integration of specific plant species within livestock facilities has been shown to reduce atmospheric contaminants such as ammonia and methane, thereby contributing to a more sustainable livestock environment while simultaneously promoting higher standards of animal welfare (Menardo et al., 2021). These phytoremediation strategies not only improve air quality but also support biodiversity by providing habitat for beneficial microorganisms and insects.

Furthermore, sustainable cattle ranching models have been proposed as viable alternatives that reconcile productivity with biodiversity conservation. These models emphasize rotational grazing systems, agroforestry integration, and the maintenance of natural vegetation buffers, all of which contribute to habitat preservation and restoration (Chará et al., 2019). By adopting such practices, livestock producers can minimize ecological disturbances, enhance soil health, and promote the conservation of native flora and fauna, ultimately supporting the long-term viability of agricultural ecosystems.

4.10. Management and system

The terms *management* and *system* emerge consistently as key concepts in the scientific literature related to livestock production. While these terms may initially appear broad or generic, their importance becomes particularly salient when contextualized within the growing discourse on the integration of animal welfare and environmental sustainability. This combined perspective seems to suggest how important is to challenge conventional production paradigms, calling for a systemic transformation in how livestock systems are designed, operated, and assessed.

The findings indicate that livestock systems should integrate productivity and economic efficiency with environmental sustainability considerations and the ethical aspects of animal welfare. However, this model is increasingly under scrutiny as concerns over climate change, biodiversity loss, and public attitudes toward animal welfare intensify (Skogen et al., 2018; Habibullah et al., 2021). Addressing these intersecting challenges requires a reconfiguration of production drivers and performance metrics, shifting the focus from maximizing output alone to optimizing across multiple sustainability dimensions.

A systemic approach to livestock management involves the deliberate coordination of diverse factors such as genetics, nutrition, housing design, health protocols, pasture management, and waste treatment within an integrated and dynamic framework (Korver, 2023). This approach moves beyond isolated interventions, advocating for a holistic view where interactions between components intend to generate synergistic benefits. For example, improvements in animal housing that reduce thermal stress can simultaneously enhance welfare, reduce disease incidence, and improve feed efficiency, thereby contributing to both economic and environmental outcomes (Shields and Orme-Evans, 2015).

Moreover, this integrated model encourages the use of adaptive management strategies, which are essential in the context of increasing environmental variability and uncertainty due to climate change. Adaptive systems are characterized by their resilience, flexibility, and capacity to learn from outcomes, allowing continuous adjustment of practices based on real-time data and emerging scientific knowledge (Canessa et al., 2016).

Critically, system-level management also implies greater stakeholder coordination across the entire value chain. This includes not only farmers and veterinarians, but also feed suppliers, policymakers, researchers, consumers, and civil society actors. Such collaboration is fundamental to ensure that innovations in management practices are socially acceptable, economically viable, and scientifically grounded. Policy support, incentive mechanisms, and education programs may also be necessary to facilitate the transition toward more sustainable systems (Dumont et al., 2024).

Rethinking livestock production through a system-based lens is no longer optional, it is essential. By promoting a multi-dimensional balance between ecological sustainability, animal welfare, and economic resilience, integrated management systems offer a pathway to ensure the long-term viability and ethical acceptability of livestock agriculture in a world facing complex environmental and societal pressures (Fernandes et al., 2019; Edwards-Callaway et al., 2024).

5. Conclusions

The livestock sector plays a critical role in shaping the health of ecosystems and the sustainability of the agri-food system. Its environmental footprint most notably through greenhouse gas (GHG) emissions, extensive land and water use, manure management, and broader resource depletion makes it a key area for reform in the context of climate change and environmental degradation. Simultaneously, the intrinsic ethical responsibility to ensure animal welfare has emerged as a parallel and equally pressing concern. These two pillars, environmental sustainability and animal ethics, represents the foundation of a modern and responsible vision for livestock production.

As demonstrated throughout this review, practices that simultaneously reduce environmental impacts while improving animal welfare can offer a dual benefit and represent the most promising path forward. This review has sought to bridge a gap in the existing literature by explicitly focusing on the intersections between strategies and interventions that seek a double perspective in livestock systems: environmental and ethical imperatives. While past research has tended to study these dimensions separately, this review highlights the potential for mutual reinforcement when both treated as integral components of system design and management. In doing so, the review contributes on multiple levels. Theoretically, it provides a consolidated overview of how these domains interact, offering a conceptual framework for understanding sustainability in livestock production beyond narrow metrics. Practically, it compiles a broad range of scientific insights and case studies that can inform and inspire stakeholders across the value chain, from farmers and veterinarians to policymakers, industry professionals and consumers.

One of the key insight is that achieving sustainability in livestock is not merely a matter of incremental change, but rather a call for systemic transformation. Sectoral actors, such as farmers, producers, and technical advisors who operate the actual strategies' implementation may primarily drive this transformation, but their efforts can only succeed within a supportive institutional and socio-political framework.

Although the search strategy was designed to ensure conceptual coherence and a focused scope, future research could strengthen the robustness and comprehensiveness of bibliometric analyses by expanding the search strategy to include a broader range of related terms (e.g., "greenhouse gas emissions," "environmental impact," or "well-being") and by incorporating a PRISMA-style eligibility screening of titles, abstracts, and full texts prior to bibliometric processing, thereby refining the corpus and further enhancing the precision of thematic mapping.

In conclusion, the dual challenge of promoting animal welfare while mitigating environmental impacts has emerged as a critical focus for modern livestock production. Evidence across multiple management domains suggests that achieving these goals simultaneously is feasible, though it requires carefully designed, context-specific strategies.

However, the transition toward more ethical, resilient, and environmentally sustainable livestock systems still arise as both urgent and attainable. It requires coordinated action across multiple scales and sectors, rooted in scientific knowledge and driven by shared values. The insights provided by the present review tend to reinforce the idea that integrating animal welfare and mitigation strategies is not only a moral imperative but also a strategic advantage, capable of delivering long-term benefits for ecosystems, economies and societies alike.

CRediT authorship contribution statement

C. Zarbà: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **R. Selvaggi:** Writing – original draft, Visualization, Conceptualization. **B. Pecorino:** Supervision, Funding acquisition. **G. Pappalardo:** Writing – original draft, Visualization, Supervision, Conceptualization. **C. Bellia:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

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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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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.indic.2026.101245.

Data availability

Data will be made available on request.

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