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Mapping the research landscape of livestock adaptation to climate change: a bibliometric review using Scopus database (1994–2023)

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Climate change threatens global livestock production through rising temperatures, erratic rainfall, and extreme events. Enhancing livestock system resilience is now a strategic priority for adaptation practitioners, policymakers, researchers, and other stakeholders committed to food security and rural livelihood sustainability. Although research on livestock adaptation is expanding, a comprehensive synthesis of its thematic evolution, performance, and knowledge gaps remains limited. This study addresses this gap through a bibliometric analysis of 3,217 publications from 1994 to 2023, retrieved from the Scopus database. Analytical tools such as Biblioshiny and VOSviewer were used for data processing and visualization. Findings reveal a consistent growth in research output, particularly post-2007, with the United States, China, and France emerging as leading contributors. Prominent authors include Sejian V., Wang X., and Li Y., while influential journals comprise Agricultural Systems, Journal of Animal Science, and Tropical Animal Health and Production. Thematic trends indicate a shift from early physiological studies (1994–2003) toward genetic diversity and adaptive traits (2004–2013), and more recently (2014–2023), a focus on heat stress, methane emissions, and sustainable breeding. The current research landscape emphasizes genetic adaptation, precision breeding, and climate mitigation strategies. Future studies should deepen the exploration of methane mitigation through genetic selection and feed innovations, while integrating indigenous knowledge and interdisciplinary approaches. Policy support and sustainable management practices will be critical to ensuring the long-term viability of livestock systems under a changing climate.

KEYWORDS

bibliometric analysis, climate change, genetic diversity, heat stress, livestock adaptation, livestock vulnerability, research trends, Scopus database

1 Introduction

Climate change presents unprecedented challenges to agricultural sustainability, particularly in the livestock sector, which is highly vulnerable to extreme weather events and shifting climatic patterns (Cheng et al., 2022). The increasing frequency of heat stress altered pathogen dynamics, and fluctuations in forage availability pose significant risks to livestock productivity and the livelihoods that depend on it (Bateki et al., 2023; Germer et al., 2023). In response to these challenges, adaptive livestock adaptation strategies have become crucial to enhance resilience and sustain production under changing climatic conditions (Casey, 2023).

The growing body of research on livestock species and breed selection in the context of climate change (Seo et al., 2010; Zhang et al., 2013; Seo, 2015) is fragmented across multiple disciplines. This fragmentation may limit cross-disciplinary collaboration and results in isolated insights. As a result, the development of comprehensive adaptation strategies that integrate perspectives from animal genetics, environmental science, and socio-economic considerations is hindered (Wanjala et al., 2023). A synthesis of the existing literature is crucial to identify effective adaptation pathways and clarify emerging trends and research priorities.

The complexity of climate-induced stressors necessitates a structured approach to synthesizing existing knowledge on livestock adaptation. Substantial efforts have been made to review the climate change adaptation literature. However, traditional review methodologies, such as systematic and narrative reviews, often struggle to capture the interdisciplinary nature and evolving landscape of this research domain (Avenali et al., 2023). Meta-analyses aggregate quantitative findings to provide overall trends (Xia et al., 2024). However, they face challenges due to inconsistencies in study methodologies and data heterogeneity, limiting their applicability in a field characterized by diverse adaptation strategies and regional contexts (Gusenbauer and Haddaway, 2020; Xia et al., 2024).

Bibliometric analysis offers an alternative for systematically analyzing large volumes of literature by identifying research trends, key contributors, and thematic structures (Avenali et al., 2023; Passas, 2024). Unlike traditional review methods, bibliometric techniques leverage citation networks and co-occurrence analysis to map the intellectual landscape, highlight research gaps, and visualize thematic evolution over time (Mirhashemi et al., 2022). This makes bibliometric analysis particularly well-suited to a fragmented field like livestock adaptation to climate change, where diverse research contributions from multiple disciplines need to be integrated into a cohesive framework.

Despite the increasing application of bibliometric methods in climate change adaptation research (Wang et al., 2018; Wu et al., 2018; Einecker and Kirby, 2020), their use in livestock adaptation studies remains largely unexplored. This study seeks to bridge this gap by applying bibliometric techniques to systematically map the research-landscape. It aims to identify dominant and emerging themes and uncover future directions and research gaps. The insights derived from this analysis will enhance the understanding of current research trends. Additionally, they will provide policymakers, researchers, and practitioners with a strategic framework to guide future research efforts. By highlighting critical knowledge gaps and emerging focus areas, this study will contribute to the development of more targeted and effective livestock adaptation strategies in response to climate change.

This study aims to conduct a bibliometric review of livestock adaptation to climate change from 1994 to 2023, employing co-occurrence and thematic evolution analysis to explore the conceptual structure of existing literature. Specifically, the study seeks to answer the following research questions:

1. What are the trends in scientific output on livestock adaptation research by year and country, and who are the most productive authors, influential journals, and highly cited papers, based on the Scopus database?
2. How have the central research themes in livestock adaptation to climate change evolved over the past three decades?
3. What does the current research landscape of livestock adaptation to climate change reveal, based on the co-occurrence of key terms and thematic clusters in literature?
4. What future research gaps and emerging themes require further investigation to enhance livestock resilience to climate change?

This paper is organized as follows: the material and methods section outlines the bibliometric analysis approach, covering research design, database, search strategy, selection criteria data validation, and data analyses framework. The results section presents key insights, complemented by visual representations of research trends and thematic patterns. The discussion contextualizes these findings within the broader scope of climate adaptation and livestock management. Subsequently, the identified research gaps are discussed, followed by the limitation of the study and the study's conclusion.

2 Materials and methods

2.1 Research design

The bibliometric research design begins with defining the research question and scope, which establish the study's focus and direction (Öztürk et al., 2024). To refine the scope and identify relevant keywords, a preliminary literature review was conducted, identifying over a thousand relevant papers and confirming the feasibility of a bibliometric analysis (Donthu et al., 2021). In line with Passas (2024), the research questions were tailored to fit the nature of bibliometric analysis. The primary question focused on assessing the performance and conceptual structure of livestock adaptation to climate change research from 1994 to 2023. As outlined by Öztürk et al. (2024), the bibliometric research design follows a structured process. After defining the research scope and questions, the next stage involves data collection, including database selection, search string formulation, and dataset filtering. This is followed by data analysis and visualization, culminating in the interpretation of results to generate meaningful insights.

2.2 Database, search strategy, selection criteria and data validation

It is crucial to search databases that have been demonstrated to be appropriate for systematic assessments of academic literature (Gusenbauer and Haddaway, 2020). Web of Science and Scopus are the most often used databases. A recent study comparing these two databases revealed that 99.11% of the journals in Web of Science are also in Scopus (Singh et al., 2021). In contrast, only 34% of the journals in Scopus are also listed in the Web of Science (Singh et al., 2021). Donthu et al. (2021) also suggest employing a single suitable database to reduce the necessity for consolidation, as reducing unnecessary tasks can minimize the risk of human errors. Thus, Scopus was selected as the central database for this review. A comprehensive electronic literature search was conducted on January 1st, 2024. This study developed an extensive and inclusive search query to retrieve all potential documents focusing on livestock in response to climate change. Figure 1 illustrates the data selection process.

An initial Scopus database search generated 8,003 results. Applying exclusion criteria, deleting 1,790 non-journal publications (e.g., book chapters, reviews, conference papers, books, editorials), resulted in 6,213 records. Further filtering for peer-reviewed journal papers published in English between 1994 and 2023 within the Agricultural and Biological Sciences and Social Sciences subject areas deleted 2,988 records, leaving 3,225 items. Prioritizing peer-reviewed journal papers enables rigorous evaluation, consistent citation indexing, and suitable for bibliometric analysis (Öztürk et al., 2024). Conversely, other publication types may lack uniformity, potentially leading to variations in citation metrics. The 1994–2023 timeline captures three decades of study following the 1992 United Nations Framework Convention on Climate Change (UNFCCC), which prioritized agricultural adaptation to climate change, and stimulated future research and policy development. Focusing on English publications accords with Scopus indexing standards and the predominance of English in global climate change research, promoting analytical consistency and comparability (Berdyyev et al., 2025; Changalima et al., 2025). The selection of publications in Agricultural and Biological Sciences and Social Sciences was intended to deliver a concentrated analysis of livestock adaptation to climate change. A final duplication verification eliminated eight records, yielding a dataset of 3,217 peer-reviewed journal articles for analysis.

The data was subsequently transformed into BibTeX and CSV forms for synthesis and analysis. In accordance with Manyike et al. (2025), data cleaning and validation encompassed guaranteeing completeness, rectifying formatting discrepancies, and standardizing keywords. Utilizing the R software (version 4.2.1), we identified absent data, rectified discrepancies, and standardized terminology (e.g., aligning "Livestock" with "Farm animals" and "Domestic animals," as well as "Heat stress" with "Temperature stress"). Furthermore, journal titles were standardized for uniformity.

2.3 Data analysis framework

The analysis was done using Biblioshiny application and VOSviewer software (Version 1.6.19). While Biblioshiny allowed the researchers to develop thematic evolution map (Aria and Cuccurullo, 2017), VOSviewer has the advantage of displaying clear network maps, determining a minimum number of keyword occurrences, and establishing a threshold (Van Eck and Waltman, 2023). This is essential when understanding the most prevalent themes in the research domain. MS Excel was also used to perform fundamental analysis and draw clear graphs of scientific production over time. Commonly employed techniques in bibliometric literature encompass performance analysis and science mapping. Performance analysis is utilized to assess the efficiency and level of recognition of various actors using bibliographic data. On the other hand, science mapping highlights the structural and intellectual patterns of the research domain (Aria et al., 2020).

Analyzing the conceptual structure is crucial for comprehending the subjects or ideas addressed within the research domain and determining which themes are the most significant and up-to-date (Aria et al., 2020). It is also crucial to establish the conceptual structure for evaluating the progress of a research topic across time (de Oliveira et al., 2019). The study also used content analysis to explore the clusters identified in the conceptual structure. This methodology is

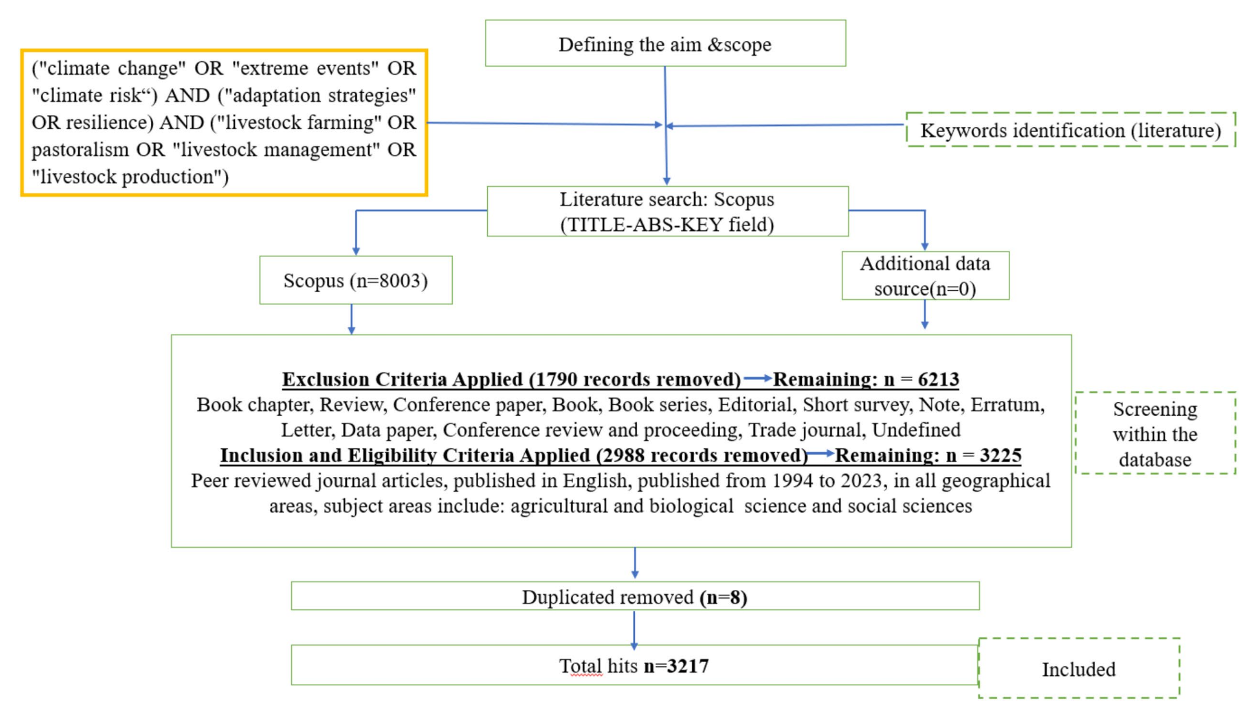

FIGURE 1
Data selection process. Source: Author's compilation.

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advantageous for analyzing patterns, understanding information, and interpreting meaning (Vaismoradi et al., 2013).

Following previous work (Aria et al., 2020; Fusco et al., 2020), the study developed a strategic thematic map that plots the keywords or themes into four quadrants, rendering the themes/keyword density and centrality rank values. Fusco et al. (2020) defined centrality as a metric that quantifies the level of interaction between a network and other networks. It is regarded as an indicator of the significance of a theme in the overall advancement of the analyzed research field. Density quantifies the network's internal robustness and indicates a theme's level of advancement.

To achieve the study's main objectives, the conceptual structure analysis was performed, with the authors' keywords being used as the focus of the analysis. The study explored the co-occurrence network of authors' keywords, and parameters for the co-occurrence network were set with a minimum of 20 occurrences, and 49 keywords met the threshold. Complete counting was employed for this analysis. Moreover, a study of thematic evolution across three distinct periods, 1994–2003, 2004–2013, and 2014–2023, was conducted, and 50 keywords were selected in the parameters. In addition, the thematic map for the recent decade was used to understand the relevance and development of themes in recent years.

Motor or engine themes refer to topics in the upper right quadrant of a thematic map (Aria et al., 2020). They are characterized by high density and centrality, indicating that the themes are thoroughly developed and crucial to the structure of the subject researched. The topics in the lower right quadrant are transversal, generic, and basic themes. Their high centrality and low density distinguish between these themes. The themes in this quadrant hold significance within the study domain, but their development needs to be improved (Fusco et al., 2020). Furthermore, they pertain to overarching subjects that intersect with several research fields, but their external relations are immaterial (Aria et al., 2020). The top left quadrant themes are referred to as niche or highly specialized and isolated motifs, characterized by a high concentration but low importance or at the borderline of the overall research field being studied (Fusco et al., 2020). Themes located in the lower-left quadrant are referred to as peripheral themes. These themes are considered emerging or decreasing and are characterized by having low centrality and low density. This means they are underdeveloped and situated at the margins or edges of the research study domain (Aria et al., 2020; Fusco et al., 2020). Therefore, in this study, the themes or keywords are analyzed depending on which quadrant they are located.

TABLE 1 Primary details about the bibliometrics dataset.

Description	Results
Main information about data	
Timespan (years)	1994:2023
Number of sources (Journals, Books, etc.)	870
Number of documents	3,217
Annual growth rate %	12.46
Document average age (years)	7.89
Average citations per doc (citations)	22.82
Document contents	
Number of keywords plus (ID)	11,209
Number of author's keywords (DE)	8,841
Authors	
Number of authors	13,960
Number of authors of single-authored docs	195
Authors collaboration	
Number of single-authored documents	212
Number of co-authors per Doc	5.39
International co-authorships %	39.14
Document types	
Number of article	3,217

Source: Author's compilation.

3 Results

3.1 Overview of the data

Table 1 presents the primary details regarding the dataset, including its size, growth rate, authorship patterns, and the content of the documents. The filtered search query yielded 3,217 articles published over 30 years (i.e., from 1994 to 2023), with an annual growth rate of 12.46% and published in 870 journals. The results indicate that in the past 30 years, the number of articles in the dataset has been steadily increasing, suggesting that research interest in the topic has been growing. The mean age of the articles in the dataset is 7.89 years. The results mean that, on average, the articles in the dataset were published approximately 7.89 years ago. This suggests that the dataset primarily contains recent publications. The results also reveal that, on average, each article in the dataset has been cited 22.82 times. This indicates the growing impact of the research within the dataset. The content of the documents includes 11,209 Keywords Plus (ID) and 8,841 Author's Keywords (DE). Lu et al. (2020) emphasize that authors typically select keywords based on their prior knowledge and experience in the field, suggesting that the chosen keywords can reflect their expertise or indicate a multidisciplinary perspective. In addition to this, these keywords are useful for identifying key themes or topics within the dataset and provide insights into the main focus areas of the research.

A total of 13,960 authors are associated with the documents in this dataset. This suggests diverse researchers are involved in the field, potentially representing different perspectives and expertise. There are 195 Authors of single authored documents and 212 single-authored documents in the dataset, meaning that most documents result from collaboration among multiple authors. On average, there are 5.39 co-authors per document. This indicates a high degree of cooperation between authors in this dataset. Approximately 39.14% of the collaborations involve international co-authorships. This suggests solid global collaboration among researchers contributing to this dataset.

3.2 Performance analysis of livestock adaptation research (1994–2023)

3.2.1 Annual and cumulative scientific production from 1994 to 2023

Figure 2 presents the annual and accumulative frequency of research publications on livestock selection in response to climate

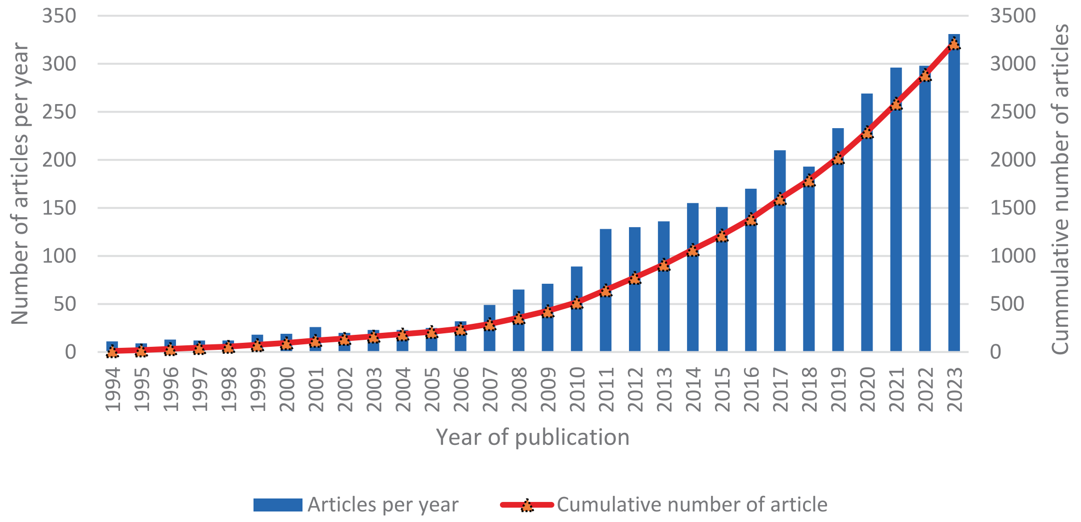

FIGURE 2
Annual and cumulative scientific production from 1994 to 2023. Source: Author's compilation.

change from 1994 to 2023. The numbers show a fluctuating trend over the years. From 1994 to the mid-2000s, there was a low volume of publications, with an average of 22 articles per year.

The most significant increase in research output appears from 2007 onwards, indicating a substantial rise in interest or emphasis on livestock selection in response to climate change. The consistent increase in publications from 2007 to 2023 suggests a growing interest in exploring livestock selection in response to climate change. This could be due to numerous factors, such as increased awareness of climate change impacts on agriculture, evolving research methodologies, and funding availability. By 2023, the cumulative total of articles published stands at 3,217.

3.2.2 Countries scientific production

Figure 3 presents a world map showing the countries' scientific production. Various tones of blue represent varying productivity levels: deep blue signifies high productivity, light blue indicates low productivity, and gray denotes an absence of articles.

The map indicates that the USA (1,559), China (682), France (607), Brazil (557), Australia (525), the United Kingdom (516), India (431), Germany (381), Spain (378), Italy (366), Canada (309), South Africa (284), Kenya (237), Ethiopia (234), Netherland (190), Mexico (133), Sweden (127), Nigeria (116), Portugal (113), and Pakistan (112) are the top 20 countries that have significant number of articles focused on the intersection of livestock and climate change. This suggests a noticeable interest or concern in comprehending and addressing the effects of climate change on livestock in these nations. The reasons for this trend differ by region; for instance, developed countries are driven by technological innovations, global economic influence, and policy leadership. African nations could be motivated by agricultural resilience, sustainability imperatives, and a commitment to international collaboration for development.

3.2.3 Three-field plot: authors-keywords-journal

Figure 4 presents a three-field plot using a Sankey diagram to highlight the interconnections between authors, keywords, and journals in the dataset. The diagram visually represents the flow of data or resources, showing the linkages between these variables (Fatehi et al., 2020; Koo, 2021; Martinez-Garcia et al., 2023; Martinez-Garcia et al., 2023). The vertical dimension of the nodes indicates the frequency of specific authors, keywords, or journals within the collaborative network, while the thickness of the connecting lines reflects the strength of these connections. The most prolific authors in the dataset can be understood in relation to the central topics they have contributed to. The key journals are based those with high volume of publications to the main topic in livestock adaptation research.

The most prolific authors in the dataset are closely tied to the central research themes in climate change and livestock adaptation. Sejian V, with the highest number of publications (16 articles), has made significant contributions to topics such as climate change, adaptation, drought, livestock, and heat stress. Authors like Wang X and Li Y, each with nine publications, predominantly focus on climate change and adaptation. The most frequently used keywords in the dataset highlight the central themes, including climate change, adaptation, heat stress, and cattle, reflecting the focus areas of these prolific authors. The consistent alignment of leading authors with these key topics underscores their influential role in advancing research in these domains. In terms of publication outlets, journals such as Agricultural Systems (41 publications), Journal of Animal Science (38 publications), and Tropical Animal Health and Production (22 publications) are prominent venues for these contributions. These journals are critical for disseminating high-impact research related to climate change and livestock adaptation.

3.2.4 The most global cited papers

Table 2 presents the most globally cited studies in the dataset, reflecting their academic influence within the adaptation and environmental change literature. Nardone et al. (2010) ranks highest with 880 citations, an annual citation rate of 55.00, and a normalized citation score of 13.76, addressing the effects of climate change on animal production and livestock sustainability. Kijas et al. (2012) follows with 637 citations (TC/year: 45.50; Normalized TC: 10.83), offering insights into genetic diversity and selection in

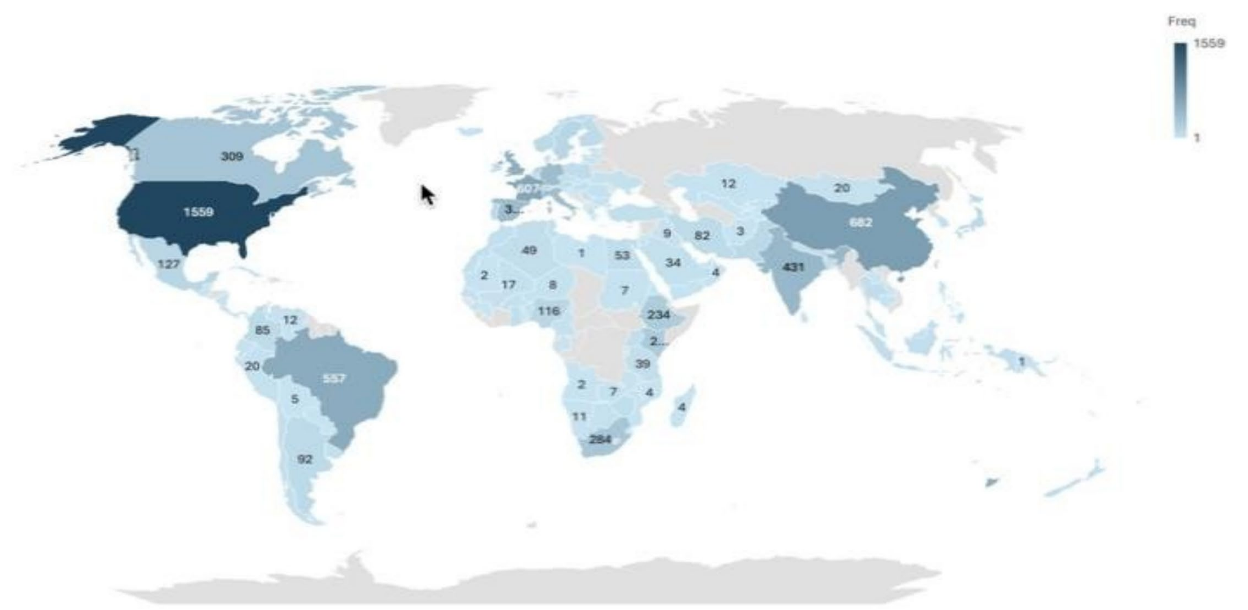

FIGURE 3
Scientific production by country. Various tones of blue represent varying productivity levels: deep blue signifies high productivity, light blue indicates low productivity, and gray denotes an absence of articles. The map was created in Excel. Source: Author's compilation.

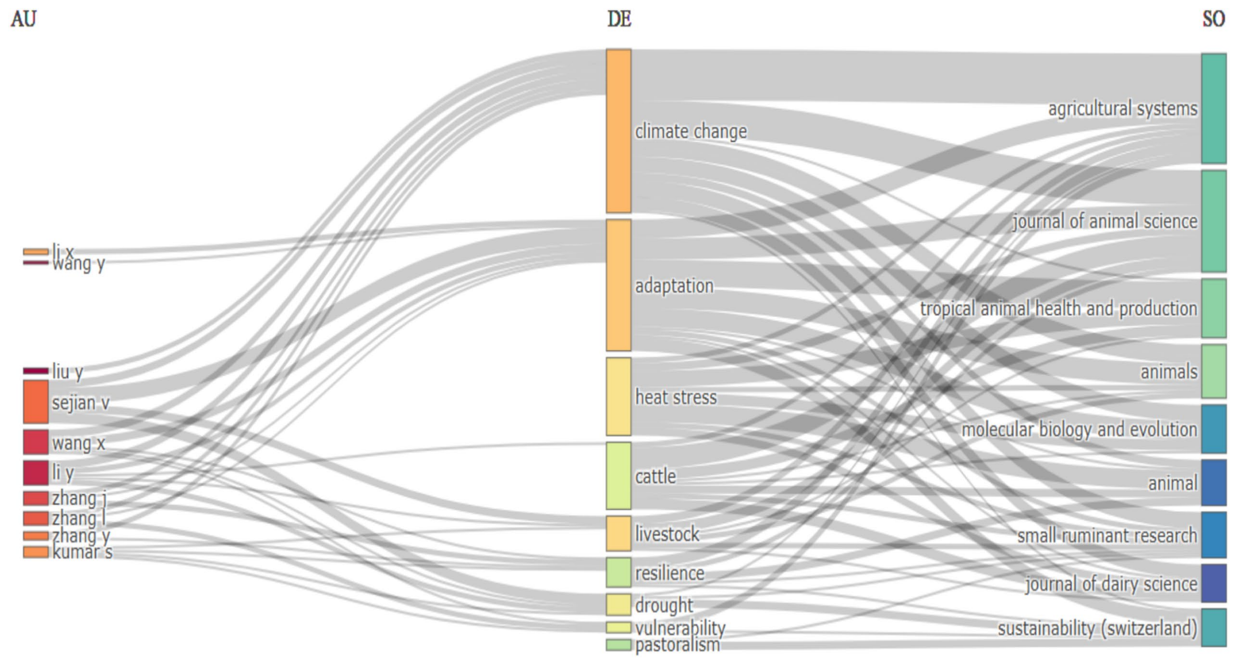

FIGURE 4
Three-field plot illustrating the interconnections between authors (left), authors' keywords (middle), and journals (right). Source: Author's compilation.

sheep. Fitt et al. (2001), with 598 citations (TC/year: 23.92; Normalized TC: 9.79), explores coral bleaching and thermal stress responses in reef corals. Deressa et al. (2011) (585 citations) examines farmer perceptions and adaptation to climate change, while Frichot et al. (2013) (545 citations) introduces LFMM, a statistical model to detect genetic loci linked to local adaptation. Other notable contributions include Féret et al. (2017) (518 citations), van Vliet et al. (2012) (483 citations), Duarte et al. (2017) (459 citations), Dong et al. (2020) (457 citations), and Rocap et al. (2002) (446 citations). Collectively, these high-impact studies illustrate the interdisciplinary and systemic nature of adaptation research.

TABLE 2 The most global cited paper on the dataset.

Paper	DOI	Total citations	TC per year	Normalized TC
NARDONE A, 2010, LIVEST SCI	10.1016/j.livsci.2010.02.011	880	55.00	13.76
KIJAS JW, 2012, PLOS BIOL	10.1371/journal.pbio.1001258	637	45.50	10.83
FITT RK, 2001, CORAL REEFS	10.1007/s003380100146	598	23.92	9.79
DERESSA TT, 2011, J AGRIC SCI	10.1017/S0021859610000687	585	39.00	10.95
FRICHOT E, 2013, MOL BIOL EVOL	10.1093/molbev/mst063	545	41.92	12.57
FÉRET JB, 2017, REMOTE SENS ENVIRON	10.1016/j.rse.2017.03.004	518	57.56	15.33
VAN VLIET N, 2012, GLOBAL ENVIRON CHANGE	10.1016/j.gloenvcha.2011.10.009	483	34.50	8.21
DUARTE CM, 2017, FRONT MAR SCI	10.3389/fmars.2017.00100	459	51.00	13.58
DONG S, 2020, AGRIC ECOSYST ENVIRON	10.1016/j.agee.2019.106684	457	76.17	21.32
ROCAP G, 2002, APPL ENVIRON MICROBIOL	10.1128/AEM.68.3.1180-1191.2002	446	18.58	4.70

Source: Author's compilation.

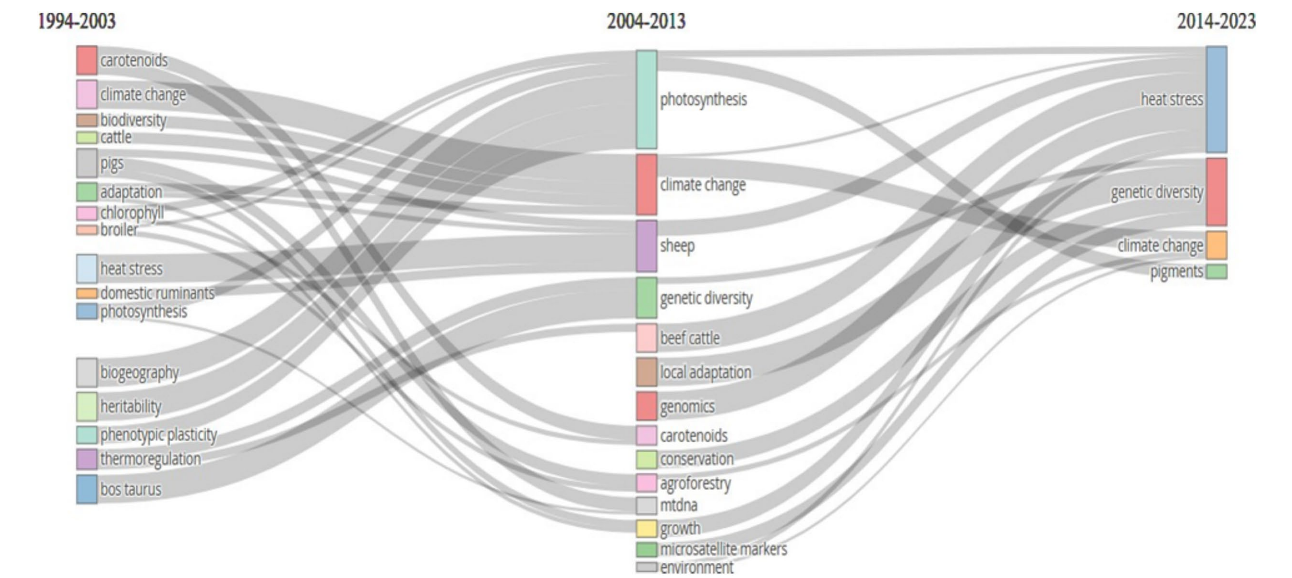

FIGURE 5
Thematic evolution diagram of 1994–2023. Source: Author's compilation.

3.3 Conceptual structure of livestock adaptation research

This section focuses on the conceptual structure of research on livestock in response to climate change, presented from the co-occurrence of keywords, thematic evolution, and thematic maps.

3.3.1 Thematic evolution of livestock adaptation research

Figure 5 presents the thematic evolution of keywords in the past three decades. In the first decade (1994–2003), research primarily focused on understanding the physiological and genetic mechanisms of adaptation to climate change. Key themes included *heat stress*, *thermoregulation*, and *phenotypic plasticity*, particularly in *cattle*, *pigs*, and *broilers*. This period also emphasized *genetic diversity* and the adaptation of livestock species, with a focus on *Bos taurus* and the role of *heritability* in breed-specific resilience. Early studies explored the impact of *climate change* on livestock, highlighting the importance of *biodiversity* and *biogeography* in understanding species distribution and adaptation to diverse climates. Additionally, nutritional factors, such as *carotenoids* and *chlorophyll*, were identified as important for supporting livestock resilience.

The second decade (2004–2013) saw a broader exploration of genetic and environmental factors influencing livestock adaptation. *Photosynthesis* emerged as a theme linked to earlier concepts of *biogeography* and *phenotypic plasticity*, suggesting an interest in the interaction between livestock and their environment. The focus expanded to include *sheep* and *beef cattle*, with increased attention on *genetic diversity*, *local adaptation*, and *genomics*. This period marked a shift toward molecular techniques, such as *mtDNA* and *microsatellite markers*, to assess genetic variation. The theme of *conservation* became more prominent, reflecting a growing awareness of the need to preserve genetic diversity for adaptation. Research continued to address *climate change* and its impacts, while *agroforestry* emerged as

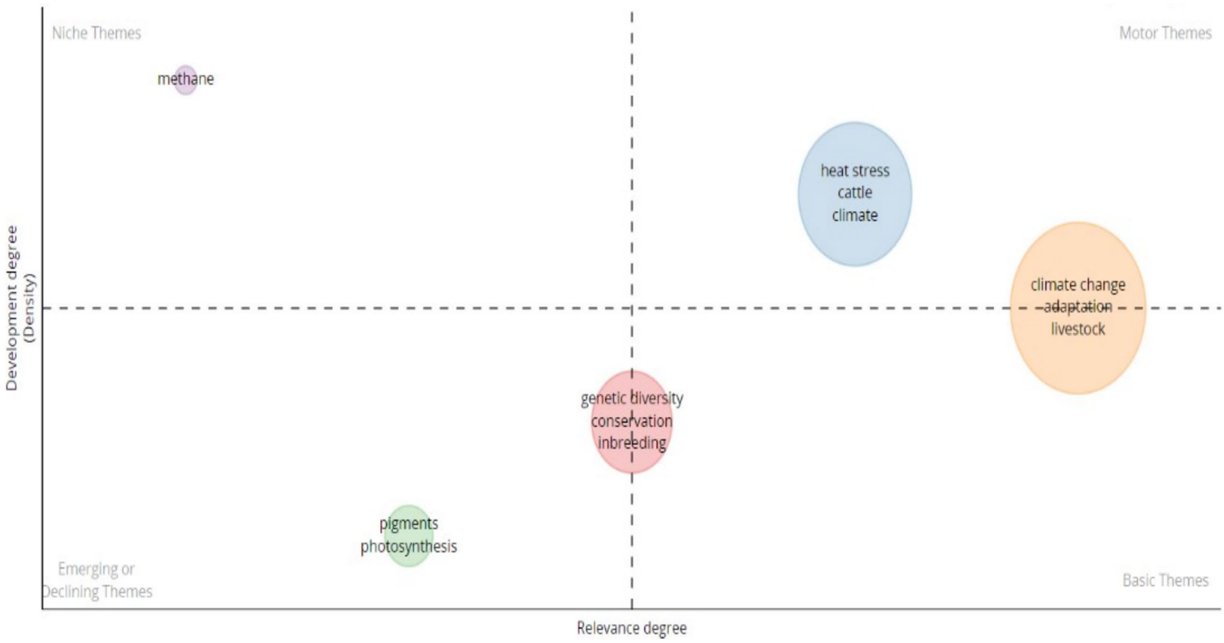

FIGURE 6
Thematic map of 2014–2023. Source: Author's compilation.

a strategy for integrating livestock management with environmental conservation.

In the recent decade (2014–2023), research further developed the themes of genetic and physiological adaptation, with *heat stress* emerging as a central concern, especially for *beef cattle* and *sheep*. Studies focused on *local adaptation*, *genomic* approaches, and *genetic diversity* to improve livestock resilience to climate-induced heat stress. The theme of *climate change* remained dominant, emphasizing its role in shaping livestock management practices. Additionally, *pigments* were identified as a potential factor in supporting livestock health, especially in response to environmental stressors. The focus on *conservation* persisted, with ongoing efforts to preserve genetic diversity for long-term adaptive capacity.

The results show a clear progression from foundational studies on physiological and genetic adaptation to more advanced approaches involving genomics, environmental sustainability, and the management of heat stress in response to climate change. Each decade contributed to the refinement of research on livestock resilience, integrating new genetic tools, environmental factors, and sustainability practices.

3.3.1.1 Livestock adaptation research development in recent years (2014–2023)

Figure 6 illustrates the thematic map for the 2014–2023 period, displaying author keywords across four quadrants based on keyword density and centrality rank values. The size of each circle represents the number of publications related to that topic, with larger circles indicating a higher volume of research. The thematic map highlights *climate change, adaptation, and livestock* as dominant themes, positioned at the intersection of basic and motor themes. Their high centrality but low density suggests that while these topics are widely relevant across the research domain, their conceptual and methodological development remains limited, indicating the need for further in-depth exploration and refinement. Additionally, *climate, cattle, and heat stress* emerge as key motor themes in the upper-right quadrant, indicating that these areas are well-developed and crucial to the research landscape. Their high centrality and density reflect a strong focus on cattle adaptation to climate-related stressors, particularly heat stress, highlighting the progress made in understanding and addressing these challenges.

A notable niche theme emerging is *methane*, reflecting a growing research focus on mitigating livestock-related greenhouse gas emissions. Its presence as a niche theme suggests that while it is a specialized area, it is gaining traction due to increasing concerns about the environmental impact of livestock production and the need for sustainable adaptation strategies. Additionally, *pigments and photosynthesis* are identified as emerging themes, suggesting a growing focus on the role of forage quality in livestock adaptation. These themes likely relate to the impact of climate change on plant growth, nutritional quality, and resilience, which directly affect livestock feed availability. Research in this area explores how improved photosynthetic efficiency and stress-tolerant forage crops can support livestock adaptation by ensuring a stable and nutritious feed supply under changing climatic conditions. Themes such as *genetic diversity, conservation, and inbreeding* are situated on the edges of emerging and basic themes, indicating that while they are gaining attention, they remain less developed but present significant opportunities for future research. This reflects a growing recognition of the importance of genetic factors in improving livestock resilience to climate change, yet their development is still at an early stage.

3.3.2 Co-occurrence's network of author's keywords

The co-occurrence network map, depicted in Figure 7, provides a visually insightful representation of the relationships among various author-defined keywords in the retrieved literature. This analytical

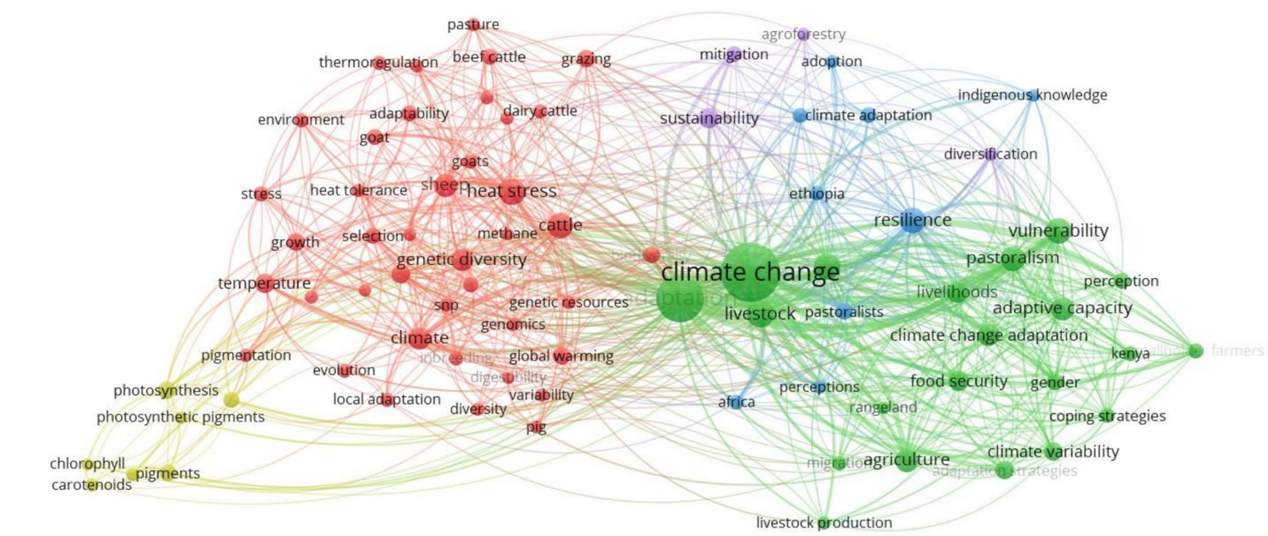

FIGURE 7
Co-occurrence network of author's keywords. Source: Author's compilation.

TABLE 3 Cluster identification and interpretation.

Cluster identification	Keywords	Concept cluster
Cluster "Red"	Adaptability, beef cattle, biodiversity, *Bos indicus*, *Bos taurus*, cattle, climate, conservation, dairy cattle, digestibility, diversity, environment, evolution, genetic diversity, genetic resources, genetic variability, genomics, global warming, goats, grazing, growth, heat stress, heat tolerance, heritability, inbreeding, local adaptation, methane, microsatellites, pasture, pig, pigmentation, population structure, reproduction, selection, sheep, stress, temperature, thermoregulation, variability	Genetic Adaptation and Breeding Strategies for Livestock in Response to Climate Change
Cluster "green"	Adaptation, adaptation strategies, adaptive capacity, agriculture, climate change, climate change adaptation, climate variability, coping strategies, drought, food security, gender, livelihood, livestock, livestock production, migration, pastoralism, perception, rangelands, smallholder farmers, vulnerability, Kenya	Climate Adaptation and Livelihood Resilience in Pastoral and Smallholder Farming Systems
Cluster "blue"	Africa, climate adaptation, Ethiopia, indigenous knowledge, pastoralists, perceptions, rangelands, resilience	Indigenous Knowledge and Climate Adaptation in African Pastoral Systems
Cluster"Mastered"	Carotenoids, chlorophyll, phenotypic plasticity, photosynthesis, photosynthetic pigment, phytoplankton, pigments	Interdisciplinary Adaptation Mechanisms in Agroecosystems
Cluster "purple"	Agroforestry, diversification, mitigation, sustainability	Sustainable Livestock Adaptation Through Integrated Agroecosystems

Source: Authors compilation from the co-occurrence network map.

approach enables the examination of dominant themes and the robustness of the relationships between these thematic elements (Scharp, 2021). The dimensions of the label and the accompanying circle for each term in this network map are determined by the frequency of occurrence within the dataset, as per the methodology established by Van Eck and Waltman (2023). Terms with greater occurrence weights are visually depicted with more prominent labels and circles, highlighting their importance in the dataset.

Notably, within the dataset, climate change (521), adaptation (310), livestock (89), heat stress (83), drought (80), resilience (77), vulnerability (76), cattle (75), pastoralism (72), and sheep (61) emerged as the most frequently occurring themes. Furthermore, the thickness of the lines connecting terms indicates the strength of the relationship or co-occurrence between them, with thicker lines representing stronger links. The analysis reveals a robust association between climate change and adaptation, suggesting a profound interdependence between these concepts within the dataset. This implies that addressing climate change is inherently linked to the imperative of adapting to its impacts, reinforcing the notion that comprehending and responding to climate change necessitates a simultaneous focus on adaptation measures.

3.3.2.1 Cluster identification and interpretation

Table 3 outlines the cluster identification and interpretation derived from the co-occurrence network map (Figure 7). The first cluster is identified as 'Red'. This cluster encompasses a comprehensive range of keywords or topics exploring the intricate relationships between heat stress, genetic factors, livestock types, adaptability, and environmental considerations to develop strategies for enhancing climate resilience in livestock farming (climate resilience and livestock management cluster red) in this cluster, heat stress and livestock species such as cattle, sheep and genetic diversity are the most occurring themes. The second cluster is identified as 'Green'. This cluster reveals the intricate relationships between climate change, adaptive measures, and sustainable livelihood strategies among livestock-producing communities (Climate Change Adaptation and Livelihood Strategies-Cluster Green). Climate change, adaptation and livestock are the most common themes in this cluster. The 'blue' cluster is indigenous knowledge for climate change adaptation and resilience among African pastoralists. It signifies the importance of indigenous knowledge in climate adaptation and resilience, particularly within African pastoral communities. Resilience is the most common theme in this cluster.

The fourth cluster is represented by the color mastered, and it indicates a thematic grouping where the main topics are photosynthetic pigments and phenotypic plasticity. The convergence of these themes suggests a specialized focus on the genotype ability of plants and animals to produce various phenotypes under different environmental conditions (photosynthetic pigments and phenotypic plasticity in livestock in the era of climate change-cluster mastered). The color purple identifies the last cluster, characterized by common themes of sustainability, diversification, and mitigation (Agroforestry Diversification for Sustainable Mitigation-cluster purple).

4 Discussion

4.1 Research performance and knowledge influence in livestock adaptation studies

Livestock adaptation to climate change research has experienced considerable growth, driven by the increasing recognition of the challenges posed by climate change, especially concerning livestock productivity and survival (Thornton et al., 2021; Habte et al., 2022). Despite this growth, developed countries continue to dominate the field due to superior resources and infrastructure (Grigorieva et al., 2023), creating a geographic imbalance as developing countries, which are more vulnerable to climate change, remain underrepresented. Addressing this imbalance requires greater investment in locally led research and the inclusion of context-specific knowledge from developing regions.

The expansion of livestock adaptation research can be attributed to several factors, including the rising frequency of climate-related shocks, the growing importance of livestock for food security and livelihoods (Godde et al., 2021) and global policy discussions surrounding the environmental impacts of livestock farming (Scoones, 2023). These elements have spurred research on climate-smart livestock systems and sustainable adaptation strategies.

Key authors and journals have consolidated the field, reflecting an increase in scholarly influence and thematic alignment with global adaptation priorities. Interdisciplinary studies, such as those focusing on ecological and farmer-centered approaches, highlight the need for systems thinking in adaptation science. While the field continues to mature, it is important to ensure that it remains inclusive, particularly by integrating research from underrepresented regions and indigenous knowledge systems, which are vital for developing comprehensive, context-sensitive adaptation strategies.

4.2 Thematic evolution in livestock adaptation to climate change research (1994–2023)

The evolution of research themes in livestock adaptation to climate change over the past three decades reveals a marked progression from basic physiological understanding to more nuanced, integrated approaches encompassing genetic, ecological, and environmental factors. Early research, particularly in the 1990s and early 2000s, was dominated by investigations into how livestock could physiologically cope with extreme climate conditions, such as heat stress (Koolhaas et al., 1999; Silanikove, 2000; Gordon, 2003). This foundational work provided essential insights into thermoregulation and phenotypic plasticity, particularly for livestock species like cattle and pigs (Brown-Brandl et al., 2001; de Jong and Bijma, 2002; Herpin et al., 2002). The increasing frequency and severity of climate-induced stressors such as droughts and heatwaves, highlighted by early reports from the Intergovernmental Panel on Climate Change (IPCC, 2007), likely provided a catalyst for this research surge, underlining the critical importance of understanding livestock resilience.

However, as the climate change discourse expanded to consider broader, multifaceted solutions, the research focus shifted after 2004. Recognizing the limitations of physiological adaptation alone, researchers began to explore the role of genetic diversity in shaping livestock resilience (Boettcher et al., 2015; Sejian et al., 2019; Tian et al., 2023). This period saw significant advancements with the application of molecular tools such as microsatellite markers and genomic technologies, allowing for more targeted interventions (van Marle-Köster and Visser, 2018; Madhusoodan et al., 2019; Sarang et al., 2024). This shift parallels broader trends in agriculture, where precision breeding is used to enhance resilience, a theme that resonates with the work of Papakonstantinou et al. (2024) on the application of genomic tools in livestock. The growing acknowledgment of the intersection between genetic traits and environmental stressors led to an integrated approach that also incorporated agroforestry and conservation practices into livestock systems. These practices helped mitigate climate change effects while simultaneously promoting sustainable production systems (Diyaolu and Folarin, 2024). The integration of these ecological practices into livestock adaptation frameworks aligns with the findings of Dawson et al. (2014), who highlighted their importance in enhancing livestock resilience and sustainability. These advancements likely played a role in shaping policy frameworks like the Paris Agreement of 2015, which emphasizes the importance of creating sustainable, climate-resilient livestock production systems (Erickson and Brase, 2019).

From 2014 to 2023, research continued to refine the themes of genetic adaptation and local resilience, but the focus also broadened to encompass new challenges such as methane emissions and environmental sustainability. This period saw a heightened emphasis on heat stress, particularly in tropical and subtropical regions, where rising temperatures threaten livestock productivity (Sejian et al., 2018). The increased focus on heat-tolerant genetic traits, in combination with dietary and genetic interventions such as antioxidants and carotenoids, reflects the growing complexity of adaptation strategies. These findings are not only significant in their own right but also align with a broader body of literature that connects livestock adaptation to climate change with global sustainability goals, as seen in studies by Di Vita et al. (2024) and Erickson and Brase (2019). Furthermore, the recognition of methane emissions as a critical concern adds a layer of environmental responsibility to the conversation, emphasizing that adaptation strategies must consider both resilience and the reduction of livestock's environmental footprint (Solomon et al., 2023).

The shift in research focus from physiological adaptation to a broader, more interdisciplinary approach-combining genetic, environmental, and ecological considerations, reflects the growing recognition that effective adaptation strategies must be holistic and integrated. By examining these evolving research themes, it becomes clear that climate change adaptation in livestock production is not just about improving heat tolerance or developing more resilient breeds. It also involves a systemic understanding that integrates genetic conservation, sustainable farming practices, and the need to address environmental impacts such as methane emissions. This evolving research trajectory underscores the importance of a multifaceted approach to livestock resilience, which is necessary for addressing the current and future challenges posed by climate change.

4.3 The current research landscape of livestock adaptation to climate change

4.3.1 Genetic adaptation and breeding strategies for climate-resilient livestock

This cluster focuses on the genetic adaptation and breeding strategies of livestock in response to climate change, emphasizing the role of heat stress, thermoregulation, and environmental factors that influence livestock performance. Heat stress is a central theme in climate resilience and livestock management literature, with significant negative impacts on livestock production. Researchers emphasize the importance of identifying climate-adaptive livestock species and breeds, particularly those that are thermotolerant and suited to specific agroecological zones, to maintain productivity (Henry et al., 2018; Sejian et al., 2018; Thornton et al., 2021). While much of the research focuses on heat stress, there is a call for more studies on how livestock adapt to cold temperatures, as the current emphasis on heat stress stems from its immediate and tangible effects on livestock wellbeing (Wanjala et al., 2023).

The selection of high-performing breeds has long been a strategy to increase cattle and sheep productivity, particularly in heat-stressed environments (Henry et al., 2018). Studies have shown that livestock species such as cattle and sheep are particularly susceptible to heat-related stressors compared to other species, such as goats, which exhibit remarkable resilience to extreme temperatures and humidity (Joy et al., 2020; Vetter et al., 2020). Goats are known for their ability to endure water scarcity, limited food resources, and severe metabolic stress, making them a robust option for regions facing climate change (Henry et al., 2018; Sejian et al., 2018). Despite intensive selection programs in domesticated livestock, significant genetic diversity remains, offering opportunities for further adaptation (Henry et al., 2018).

Natural selection has favored breeds with enhanced heat tolerance, particularly in tropical and subtropical regions, where they also demonstrate superior growth and reproductive capabilities under challenging environmental conditions marked by inadequate nutrition and heightened disease and parasite pressure (Henry et al., 2018; Joy et al., 2020; Vetter et al., 2020). Certain livestock breeds, even within the same species, show varying degrees of resilience to heat stress due to genetic differences (Gantner et al., 2017). However, with ongoing climate change, producers in heat-stress-prone areas may need to reassess the breeds and genetic compositions they rely on. Research into the susceptibility of dairy and beef cattle, particularly the *Bos indicus* and *Bos taurus* breeds, to heat stress reveals that dairy cows are more vulnerable than beef cattle, and temperate *Bos taurus* breeds are more susceptible than tropical *Bos indicus* cattle (Nyamushamba et al., 2017; Polsky and Von Keyserlingk, 2017).

Boettcher et al. (2015) suggest that genetic changes in livestock will play a critical role in their adaptation to climate change, with traits such as resilience to extreme climatic conditions and the ability to thrive on low-quality diets becoming increasingly important in harsh environments. However, the genetic diversity of indigenous breeds is being eroded due to indiscriminate crossbreeding and institutional policies that favor high-producing exotic breeds in smallholder farming systems (Nyamushamba et al., 2017; Wanjala et al., 2023). This loss of genetic diversity presents a significant challenge for livestock adaptation to changing environmental conditions. Conservation efforts for indigenous breeds are crucial for maintaining genetic diversity, which is essential for species' adaptation to emerging disease threats and shifting ecological conditions (Molotsi et al., 2019). Moreover, maintaining genetic diversity aligns with international commitments, such as Sustainable Development Goal 2.5, which emphasizes the importance of genetic diversity in domesticated plants and animals (Wanjala et al., 2023). Therefore, cluster underscores the importance of genetic diversity, breed selection, and conservation efforts in developing livestock that can withstand the challenges posed by climate change. The resilience of livestock populations depends not only on genetic adaptation but also on the preservation of indigenous breeds that offer valuable traits for adapting to a rapidly changing environment.

4.3.2 Livelihood resilience in pastoral and smallholder farming under climate change

The co-occurrence network highlights the interconnectedness of key themes such as climate change, adaptation, and livestock, signaling a significant body of research on the impact of climate change on livestock production and the necessary adaptation strategies. Several studies emphasize the importance of practical, multi-dimensional adaptation strategies to mitigate the harmful effects of climate change. For instance, Henry et al. (2018) argues that because climate change impacts are complex and multifaceted, adaptation strategies must encompass a variety of approaches to protect ruminant production systems. Similarly, Zhang et al. (2017) stresses the importance of modifying land use and feeding practices as part of the adaptation process.

Sejian et al. (2015) expand on this by advocating for both adaptation and mitigation strategies, such as developing breeds that are less sensitive to climate fluctuations and integrating modern technologies to enhance livestock resilience. Additionally, Seo and

Mendelsohn (2008) provide an example from African livestock management, where farmers are transitioning to more heat-tolerant species as a direct response to climate change. Taruvinga et al. (2013) further reinforce this point, highlighting the adaptive strategies of rural South African farmers, who adjust their livestock combinations as a coping mechanism for climate variability. Collectively, these studies emphasize the need for diverse, proactive adaptation strategies to address the challenges posed by climate change.

The literature also extensively examines the vulnerability of pastoralists and smallholder livestock farmers, focusing on critical issues such as food security, climate change perceptions, and adaptive capacity. Research has identified that these groups face significant challenges, including water and fodder scarcity, increased heat stress, and biodiversity loss (Wakayo and Dedefo, 2019; Faisal et al., 2021). To address these challenges, farmers have developed a range of coping strategies, including livestock migration, integrating crop and livestock production, destocking, splitting herds, and utilizing forest products as food sources (Silvestri et al., 2012; Belay et al., 2017; Kgosikoma et al., 2018; Wakayo and Dedefo, 2019). However, Karimi et al. (2018) notes that herder families in southwest Iran struggle to adapt despite employing traditional strategies, due to the low adaptability of their livestock. Likewise, Bewket (2012) reports that smallholder farmers in Ethiopia's central highlands are increasingly aware of the negative impacts of rising temperatures and decreasing rainfall on agriculture and livelihoods.

Despite the development of various adaptation strategies, challenges remain. Limited access to resources, education, and institutional support often undermine the effectiveness of these strategies (Silvestri et al., 2012; Tessema, 2019). Nonetheless, there is strong awareness of climate change impacts within these communities, coupled with a notable willingness to adapt (Abdou et al., 2022). This underscores the need for targeted policy interventions and support mechanisms to enhance the resilience of livestock farming communities (Belay et al., 2017; Kgosikoma et al., 2018). Riché et al. (2009) highlight the crucial role of NGOs, donors, and governments in strengthening the adaptive capacity of pastoralists, particularly in Ethiopia's Borana region and Somalia. Overall, these studies underscore the urgent need for tailored support to help vulnerable communities effectively address the challenges posed by climate change.

4.3.3 Indigenous knowledge for climate resilience in African pastoralism

This cluster highlights the crucial role of indigenous knowledge in enhancing climate resilience among African pastoralists. Pastoral communities, particularly in regions like Ethiopia, rely on traditional knowledge to select livestock breeds with traits such as heat tolerance, drought resistance, and disease resilience, ensuring their adaptability to evolving climate stressors. Effective rangeland management, informed by indigenous knowledge, is essential for sustaining livestock production under changing climatic conditions.

Indigenous knowledge encompasses weather prediction, climate risk assessment, and adaptation strategies, offering valuable insights to enhance climate change responses (Filho et al., 2023). It provides practical coping mechanisms and informs adaptation options for managing rangelands (Oba, 2012; Ahmed and Bihi, 2019). However, the socially constructed nature of indigenous knowledge may sometimes conflict with scientific perspectives. Despite this, integrating indigenous and scientific knowledge is crucial for developing participatory and cost-effective climate adaptation strategies (Ajani et al., 2013; Makondo and Thomas, 2018). Scholars advocate for incorporating indigenous knowledge into climate policies to enhance the sustainability of rangeland management and the resilience of pastoral communities (Kasali, 2011; Etchart, 2017; Makondo and Thomas, 2018). The integration of traditional knowledge with modern approaches offers a comprehensive framework for addressing climate challenges in pastoral systems.

4.3.4 Interdisciplinary adaptation mechanisms in agroecosystems

The concept cluster sheds light on the emerging interdisciplinary approach, where plant adaptation mechanisms, such as energy absorption and environmental response, are conceptually linked to livestock phenotypic plasticity in the context of climate change adaptation. Phenotypic plasticity, defined as the ability of an organism to alter its phenotype in response to environmental factors (Rovelli et al., 2020), plays a critical role in both plant and livestock systems as they adapt to climate stressors. This intersection suggests a broader understanding of resilience across ecosystems, where the selection of traits like heat tolerance, water-use efficiency, and disease resistance in livestock parallels the adaptive processes in plants (Roulin, 2014; Ramírez-Valiente et al., 2015). The comparison emphasizes the interconnectedness of agricultural systems, reinforcing the need for an integrated approach to climate change adaptation that accounts for both plant and animal responses. Additionally, the inclusion of plant-related terms in livestock adaptation research reflects a growing recognition of interdisciplinary studies, expanding the scope of climate change adaptation strategies in agroecosystems.

4.3.5 Integrated agroecosystems for sustainable livestock adaptation

Agroforestry, as a sustainable land-use system integrating trees, crops, and livestock, offers critical strategies for climate change adaptation in livestock systems. It provides environmental benefits like carbon sequestration, biodiversity conservation, and microclimate regulation while supporting livestock through shade, diversified feed, and stable water supplies (Dawson et al., 2014; Seneviratne et al., 2015; Amrutha et al., 2023; Bogale and Bekele, 2023). The interconnectedness of livestock and crop systems underscores the importance of multi-faceted approaches, where agroforestry enhances resilience and reduces vulnerability to climate stressors. However, further research is needed to fully realize its potential in supporting diversified and sustainable agricultural practices in the livestock sector (Dawson et al., 2014).

4.4 Identified knowledge gaps in livestock adaptation to climate change research

Future research on livestock adaptation to climate change should address several critical areas to improve the resilience of livestock systems. One of the foremost priorities is the mitigation of methane emissions, which has emerged as a significant environmental concern. Despite growing recognition of its climate impact, methane's full environmental consequences remain underexplored. Future studies should investigate genetic selection for lower methane-emitting animals and explore sustainable feed additives. Furthermore, research is needed on strategies that can reduce methane emissions without compromising livestock productivity, a key challenge that has yet to be sufficiently addressed.

Another promising area for future exploration involves the role of pigments and photosynthesis in enhancing livestock resilience. These biological mechanisms offer potential avenues for improving livestock adaptation to climate change, yet our understanding of their precise contribution remains limited. Future studies should focus on elucidating how these processes can be leveraged for climate adaptation, and how they may inform new breeding strategies aimed at enhancing resilience across diverse livestock species.

In addition, genetic diversity plays a central role in ensuring long-term adaptability to climate change. While much research has focused on preserving genetic diversity, future studies should explore the integration of genetic traits with physiological mechanisms, such as phenotypic plasticity, to improve climate resilience. This integrated approach could inform more precise breeding programs tailored to enhance the adaptive capacity of livestock. While genetic traits have received considerable attention, the role of physiological mechanisms in adaptation remains underexplored, leaving a significant gap in understanding. Moreover, future research should focus on how to maintain genetic diversity in marginalized or endangered breeds, which may hold valuable adaptive traits for climate resilience.

Heat stress remains a dominant concern in livestock adaptation research. However, studies should be expanded to include a broader range of climate challenges, such as drought, cold stress, and disease outbreaks, to assess the full scope of livestock vulnerability. While much of the research has centered on cattle and sheep, species such as pigs and poultry, which may have unique vulnerabilities and adaptation mechanisms, have been largely neglected. Targeted research on these species is crucial to understanding their specific responses to various climate stressors and developing tailored adaptation strategies.

Incorporating livestock adaptation strategies into broader climate change adaptation frameworks is another critical direction for future research. It is essential to explore how livestock systems can contribute to agricultural resilience and integrate with broader climate change mitigation efforts. A key research gap lies in understanding how livestock adaptation intersects with ecosystem health, including the management of pasture health, biodiversity, and water resources. These areas remain insufficiently addressed, and future studies should investigate how livestock systems interact with these broader ecosystem dynamics to promote both climate resilience and environmental sustainability.

The integration of indigenous knowledge into livestock adaptation strategies represents another underexplored area. Indigenous knowledge, particularly in pastoralist systems, offers valuable insights into climate adaptation that could complement modern scientific approaches. Future research should explore how this traditional ecological knowledge can be integrated into contemporary livestock management practices, improving climate resilience in pastoralist communities. By bridging the gap between traditional knowledge and modern science, researchers can develop more contextually appropriate and culturally sensitive adaptation strategies.

Research into agroecosystem integration is also crucial for enhancing climate resilience. Practices such as agroforestry and sustainable livestock management offer synergistic benefits but remain under-researched in the context of livestock adaptation. Future studies should examine how integrated agroecosystems can enhance both livestock resilience and broader environmental sustainability. Understanding how these integrated practices can be adapted to changing climatic conditions will be essential for promoting long-term ecological health and livestock system resilience.

Future research should also address underexplored themes such as cold stress, disease resilience, and the role of less-studied species like pigs and poultry in climate adaptation. Finally, there is a need for more interdisciplinary research that integrates indigenous knowledge systems, agroecosystem management, and socio-economic dimensions. Such approaches can contribute to the development of inclusive, context-specific, and sustainable livestock adaptation strategies in response to climate change.

Finally, addressing the complex challenges of livestock adaptation to climate change requires an interdisciplinary approach. The intersection of animal science, environmental science, and social science offers a comprehensive framework for understanding livestock resilience in a climate-impacted world. Future research should prioritize interdisciplinary studies that examine the socio-economic implications of livestock adaptation, particularly in marginalized communities. Understanding the roles of gender, food security, and socio-cultural factors will be critical for developing inclusive and equitable adaptation strategies that address the diverse needs of smallholder farmers and pastoralist systems.

5 Limitations and future research implications

While this study provides valuable insights into the evolution of livestock adaptation research, some limitations should be acknowledged. First, the analysis was confined to English-language publications indexed in the Scopus database. This may have excluded relevant studies published in other languages or indexed in alternative databases such as Web of Science, PubMed, or Google Scholar, potentially underrepresenting contributions from non-English-speaking regions. Future studies should consider incorporating multilingual sources and multiple databases to achieve a more globally representative view. Second, although bibliometric methods are effective for mapping research trends and thematic structures, they do not assess the quality, depth, or contextual relevance of individual studies. The interpretation of keyword clusters and thematic evolution relies on metadata rather than full-text analysis. Combining bibliometric approaches with systematic or scoping reviews would enrich the analysis and provide deeper insights into the intellectual and conceptual foundations of the field.

6 Conclusion

This study aimed to map the evolution and thematic direction of livestock adaptation research in response to climate change between

1994 and 2023. The findings reveal a dynamic shift from early physiological investigations toward more integrated and genetic-based approaches, including the use of genomic tools, sustainable management practices, and agroecological innovations.

While research output and diversity have grown substantially, the study also underscores critical gaps, particularly the limited contextualization of adaptation strategies to the realities of smallholder and resource-constrained farmers. Key thematic trends such as genetic heat resilience, integration of indigenous knowledge, and interdisciplinary approaches remain central, but their practical uptake depends on how well they align with farmers' adaptive capacities and local systems.

To move forward, livestock adaptation research must prioritize inclusive, farmer-informed strategies that reflect regional variability and socio-economic constraints. Enhancing farmer capacity through improved access to resources, knowledge systems, and localized innovations is essential for translating scientific progress into tangible adaptation outcomes. Therefore, a holistic, farmer-centric research approach is vital for building resilient livestock systems under growing climate uncertainty.

Author contributions

JM: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Validation, Visualization, Writing – original draft, Writing – review & editing, Project administration. AT: Funding acquisition, Resources, Supervision, Validation, Writing – review & editing. BA: Conceptualization, Data curation, Formal analysis, Methodology, Writing – review & editing.

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Generative AI statement

The author(s) declare that Gen AI was used in the creation of this manuscript. During the preparation of this work, the author(s) used AI (Quillbot, Wordtune, and Grammarly) to improve readability and language. After using this tools/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

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