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Climate-smart livestock production: strategies for enhanced sustainability and resilience

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Climate-smart livestock production: strategies for enhanced sustainability and resilience

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Editorial: Climate-smart livestock production: strategies for enhanced sustainability and resilience

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Editorial on the Research Topic
Climate-smart livestock production: strategies for enhanced sustainability and resilience

Introduction

Livestock production systems are one of the most vulnerable sectors of the global agricultural landscape, which continues to change due to climate change (1–3). Animal health, productivity, and the overall sustainability of farming systems are increasingly at risk due to extreme weather events, prolonged heatwaves, shifting disease dynamics, and depleted natural resources (4–6). Consequently, the concept of climate-smart livestock production has received attention as an approach that promotes environmental sustainability, productivity, and adaptability to climate change. Climate-smart livestock production refers to an integrated and adaptive approach to animal production that aims to reduce greenhouse gas emissions, enhance resilience to climate variability, and sustainably increase productivity while ensuring animal welfare, food security, and environmental sustainability.

Eleven interdisciplinary contributions from 42 authors from various continents were received under the Research Topic *Climate-smart livestock production: strategies for enhanced sustainability and resilience*. These consist of reviews, conceptual viewpoints, and original research articles that discuss problems and solutions in the livestock industry. The contributions can be grouped into four sub-themes: Education and Research Trends, Policy and Financial Resilience, Technological Innovations and Management, and Nutrition and Physiology.

Physiology and nutrition as primary adaptation techniques

One of the central themes in climate adaptation is nutrition. In order to reduce environmental effects and increase productivity, Fushai et al. highlighted climate-smart livestock nutrition in semi-arid Southern Africa. The authors advocated the strategic and sustainable use of Indigenous feed resources. Regarding physiological responses,Greene et al. investigated the effects of heat stress on the function of the ileal barrier in broilers that were divergently selected for water efficiency. They identified vulnerabilities specific to each genotype that indicate a compromise between gut integrity and water conservation. The potential of nutraceuticals in climate-resilient poultry nutrition was also highlighted by Sumanu et al., who showed the positive effects of probiotics and ascorbic acid in reducing heat stress in broilers. Additionally, Deniz et al. examined the effects of climate on equine hematology over 3 years in different species and reported a correlation between seasonal climate variation and physiological changes that are important for managing equine welfare in hot climates.

Innovations in technology and management systems

Numerous studies highlight the contributions of systems-level management and technological innovation to achieving climate goals. Neculai-Valeanu et al. emphasized how digital technologies, like wearables and precision livestock monitoring, can improve the health and welfare of animals. The authors revealed that data could to drive the shift to precision livestock production. Furthermore, using life cycle assessment models, the findings of Thompson et al. projected that the U.S. beef and dairy industries could achieve climate neutrality by 2050 by combining interventions such as methane reduction, feed improvement, manure management, and soil carbon sequestration. In a similar vein, Sun and Wang examined carbon emissions in China's beef sector and discovered geographical differences associated with production intensity and policy. These findings are beneficial to national mitigation strategies.

Financial and policy tools for climate resilience

Economic instruments and policy frameworks are also essential for fostering resilience. Agroforestry, integrated livestock-crop systems, and local breeding programs are among the adaptation strategies for livestock development in low- and middle-income countries (LMICs) that Bashiru and Oseni have elucidated. Extension agents and development professionals will find their recommendations helpful. Melketo et al. evaluated farmers' readiness to embrace index-based livestock insurance (IBLI) in Ethiopia (Melketo et al.). The study revealed that adoption was influenced by trust, awareness, and experience of climate shock, highlighting IBLI's potential as a risk-buffering tactic for pastoral communities.

Trends in education, research, and future paths

Priorities for research and education are also captured in this Research Topic. In the context of climate-smart livestock management, Ritter et al. investigated different ways to improve veterinary-producer relationships. They opined that developing collaborative capacity required mutual trust, communication skills, and climate literacy. Lastly, a bibliometric analysis of worldwide research trends in livestock and climate change from 1994 to 2023 was presented by Manyike et al.. Future funding and research efforts will be guided by their findings, which have revealed significant gaps, emerging themes, and a growing scholarly output, particularly in low-income regions.

In summary, this Research Topic presents multidisciplinary, innovative approaches to climate-smart livestock production. It places a strong emphasis on systems thinking across the fields of education, policy, technology, nutrition, and genetics. The contributions demonstrate how science and innovation can promote sustainability in livestock systems, ranging from traditional knowledge to sophisticated analytics. Aligning research, policy, and practice is more crucial and needed than ever as climate variability increases. Overall, this Research Topic will stimulate workable solutions and legislative initiatives that promote climate resilience and sustainable development on a global scale.

The complete Research Topic can be accessed at https://www.frontiersin.org/research-topics/65411.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Evaluating the efficacy of probiotics and ascorbic acid as anti-stress agents against heat stress in broiler chickens

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Heat stress poses a substantial challenge to poultry production worldwide, highlighting the urgent need for effective management strategies. This study investigated the efficacy of probiotics (*Saccharomyces cerevisiae*) and ascorbic acid as antistress agents using cloacal and body surface temperatures (CT and BST) as heat stress biomarkers in broiler chickens. A total of 56 broiler chicks were used for the experiment and were divided into four distinct groups: control, probiotics (1 g/kg of feed), ascorbic acid (200 mg/kg of feed) and the combination of probiotics and ascorbic acid (1 g/kg and 200 mg/kg of feed, respectively). The study lasted 35 days; measurements were taken for ambient temperature (AT), CT, and BST. The ambient temperature in the pens consistently exceeded the thermoneutral zone (TNZ) established for broiler chickens. The CT values for broiler chickens in the probiotic group were significantly lower ($p < 0.05$) compared to the control group. Additionally, the BST values in the probiotic and probiotic + ascorbic acid groups were significantly lower ($p < 0.05$) than those in the control group. The findings suggest that incorporating probiotics, with or without ascorbic acid, can effectively reduce CT and BST values in broiler chickens thereby, enhancing thermoregulation when compared to the control group. This implies that using probiotics in poultry diets may enhance health and growth performance, potentially leading to better feed efficiency and reduced reliance on antibiotics. Implementing these dietary strategies could improve the productivity and welfare of broiler chickens in commercial settings.

KEYWORDS

heat stress, cloacal temperature, body surface temperature, probiotic, ascorbic acid, thermoregulation

1 Introduction

Agricultural systems around the globe are increasingly facing negative consequences due to climate change. This is manifested in rising global temperatures and changing weather patterns (1). According to Sundstrom et al. (2), heightened temperatures, unpredictable rainfall, prolonged droughts, and more frequent extreme weather events pose significant threats to food production and security. These alterations disrupt the delicate balance of ecosystems, affecting the growth, development, and productivity of crops and livestock (3). In particular, high ambient temperatures during the summer months often lead to heat stress in broiler chickens (4, 5). This issue has intensified due to both geographical factors and the wider impacts of global warming, making it a critical concern in poultry production (6, 7). The thermoneutral zone (TNZ) refers to the range of environmental temperatures in which broilers can maintain a balance between evaporative heat loss and metabolic heat production, ensuring their comfort and health (8). When temperatures exceed this zone, the welfare of broilers can deteriorate significantly. In tropical and subtropical regions, the combination of high relative humidity and elevated temperatures creates substantial challenges for effective broiler management (3). Increased temperatures and humidity can lead to heat stress, adversely affecting the growth performance and overall efficiency of broiler chickens (9, 43).

Although broilers in temperate climates typically thrive in intensive farming systems with controlled microclimatic conditions, this is not always true in less developed regions, where broiler farming depends on natural ventilation and open-sided housing (10). These conditions make broilers more susceptible to heat stress (11). Cloacal temperature (CT) is a valuable physiological marker for assessing heat stress, reflecting the core body temperature of the birds (12). Meanwhile, body surface temperature (BST) provides insight into how effectively broilers manage heat dissipation through mechanisms like vasodilation, which helps to release heat through the body's surface (13). To combat the detrimental effects of thermal stress, dietary interventions can play a critical role (8, 14). Supplements with anti-stress and antioxidant properties, such as probiotics and ascorbic acid, have shown promise in enhancing broiler productivity and resilience (6, 15, 16).

Probiotics are microorganisms that have the ability to fight certain pathogens within the gastrointestinal tract of chicken (17–19, 41). They are generally given as feed additives in sufficient amounts and highly beneficial effects have been noticed in the field (20). Certain bacterial and fungal species have presented promising results as efficient probiotics in both animals and chicken (21, 22). Yeasts like *Saccharomyces cerevisiae* are highly beneficial in stabilizing the gut microbiota along with reducing the risk of disease occurrence (23, 24). Probiotics, such as *Saccharomyces cerevisiae* play a crucial role in alleviating heat stress in broiler chickens through several mechanisms (25). Ascorbic acid, widely recognized as vitamin C, is a powerful antioxidant that plays a crucial role in protecting cells from oxidative stress caused by free radicals. Its potential benefits in managing heat stress, particularly in livestock and poultry, are well-documented (26). While probiotics and ascorbic acid offer distinct benefits, their effectiveness as anti-stress agents may vary based on dosage, administration method, and the specific conditions of the poultry environment (27–30). Their impact on the hypothalamic–pituitary–adrenal axis has made them an effective agent for combating stress, leading to improved resilience and overall well-being by modulating the body's stress response mechanisms. This study examined the effectiveness of probiotics (*Saccharomyces cerevisiae*) and ascorbic acid as agents to alleviate stress in broiler chickens. It utilized CT and BST as biomarkers for heat stress to assess their impact. To our knowledge, no research has evaluated the combined effects of the probiotic *Saccharomyces cerevisiae* and ascorbic acid in mitigating heat stress impacts on broiler chickens at the time this study was conducted. The objective of this study was to assess the anti-stress effects of both the probiotic and ascorbic acid in broiler chickens during the challenging summer months, using CT and BST as biomarkers for heat stress.

2 Materials and methods

2.1 Environmental conditions in the experimental sites

After the brooding period, the chickens were exposed to the challenging thermal conditions typical of the hot summer season in Pretoria, South Africa. These conditions were characterized by high relative humidity, exceeding 65–70%, and elevated ambient temperatures exceeding 18–26°C, which induced heat stress in chickens raised in tropical climates (6).

2.2 Experimental animals and management

Ceramic heaters set to 34°C were employed to provide the necessary warmth during the brooding period for the broiler chicks, which lasted 14 days. To maintain biosecurity, footbaths containing F10 Super Concentrate (Health and Hygiene (Pty) Ltd., Roodepoort, South Africa) at a dilution of 1:500 were provided. Additionally, all personnel were required to use designated footwear and clothing. Fifty-six chickens were used in this study and divided into four groups of 14. Group I served as the control, Group II received the probiotic, Group III was given ascorbic acid, and Group IV received both the probiotic and ascorbic acid. Probiotics and ascorbic acid were incorporated into the chickens' feed from D1 to D35. They were administered at a dose of 1 g/kg of feed (31) and 200 mg/kg of feed (15), respectively both singly and in combination. Each broiler chicken was individually marked with color-coded markings and wing tags to ensure precise record-keeping.

2.3 Experimental measurements

2.3.1 Thermal environmental parameters

An electronic sensor (Hobo) was installed in the poultry pen to continuously monitor ambient temperature (AT) and relative humidity (RH). The chickens were brooded for 2 weeks at 34°C as earlier mentioned, after which they were exposed to the naturally occurring ambient conditions. On D21, D28, and D35 of the experiment, AT and RH measurements were recorded twice daily to capture the diurnal variations. The temperature-humidity index (THI) was calculated using the following formula:

$$THI = (1.8 \times AT + 32) - (0.55 - 0.55 \times RH) \times [(1.8 \times AT + 32) - 58]$$

where THI = temperature-humidity index, AT = Ambient temperature (°C) and RH = Relative humidity (%) (6).

2.3.2 Cloacal and body surface temperature measurements

A digital clinical thermometer (Zhengzhou AiQURA Intelligent Technology Co., Ltd., China) was used to record CT on D21, D28 and D35 of the study. These CT measurements were taken concurrently with recordings of AT and RH. For BST measurements, seven broiler chickens from each group were randomly selected on

D21, D28 and D35 of the study. Body surface temperature was assessed using an infrared thermometer (Rutland Industries, South Africa).

2.3.3 Calculation of convective and conductive heat loss

Sensible heat loss by convection and conduction to the environment in broiler chickens was calculated using a modified formula (32):

$Q_c = A_s \times h\ (T_s - T_{at})$

Where:

Q_c is conductive and convective heat loss;

A_s is the surface area of the bird (m^2) ($A_s = 3.86 \times MC^{0.74}$);

MC is the body mass of the broiler chicken (kg);

hc is the heat transfer coefficient ($hc = 0.336 \times 4.184 \times (1.46 + \sqrt{V_{AR} \times 100})$);

V_{AR} is air velocity ($V_{AR} = 0$);

T_s is the average surface temperature of birds (°C) and

T_{at} is the ambient temperature (°C).

2.4 Statistical analysis

The data were log transformed to achieve a normal distribution, which is essential for the validity of subsequent analyses. After the data were normalized, they underwent repeated measures analysis of variance (ANOVA), to determine differences between the means of the control and treatment groups. Tukey's HSD test was employed, with significance set at 0.05. The analysis was performed using SPSS Statistics for Windows, Version 27 (Armonk, NY: IBM Corp).

3 Results

3.1 Ambient temperature and cloacal temperature responses

On D21, D28, and D35 of the study period, AT values exceeded the thermoneutral zone recommended for chickens (Table 1). On D21, the CT in the probiotic group was significantly lower (40.84 ± 0.05; $p < 0.05$) at 19:00 h which was the last reading for the day when compared to the control group (41.69 ± 0.18). Additionally, at 7:00 h (which was the start of the procedure) of D35, the CT values recorded in the probiotic, ascorbic acid and the co-administered groups were significantly lower (40.36 ± 0.18; 40.97 ± 0.15 and 41.01 ± 0.16, respectively; $p < 0.05$) than those for the control group (Table 2).

3.2 Body surface temperature (BST)

On D21, D28 and D35, broiler chickens in the probiotic, ascorbic acid and the co-administered groups exhibited significantly higher ($p < 0.05$) temperatures in the comb and wing due to heat dissipation to the surrounding. There was a significantly lower ($p < 0.05$) temperature in the foot, back and head of the broiler chickens in the treatment group in comparison with the control during the study (Table 3).

TABLE 1 Temperature and humidity indices on days 21, 28, and 35 of the study.

Time (h)	DBT (°C)	RH (%)	THI
7:00	27.67 ± 0.33 (27–28)	83.33 ± 2.19 (79–86)	27.33 ± 0.32 (26.7–27.7)
9:00	28.33 ± 0.33 (28–29)	74.67 ± 2.19 (72–73)	27.80 ± 0.31 (27.4–28.4)
11:00	28.67 ± 0.33 (28–29)	79.00 ± 0.00 (79)	28.27 ± 0.33 (27.6–28.6)
13:00	33.33 ± 1.67 (30–35)	81.67 ± 4.33 (73–86)	32.80 ± 1.70 (29.4–34.6)
15:00	34.00 ± 1.00 (33–36)	84.00 ± 2.00 (80–86)	33.40 ± 1.00 (32.4–35.4)
17:00	31.33 ± 0.67 (30–32)	80.00 ± 0.00 (80)	30.87 ± 0.64 (29.6–31.6)
19:00	28.33 ± 0.33 (28–29)	77.00 ± 2.00 (73–79)	27.87 ± 0.27 (27.6–28.4)
Overall mean ± SEM	30.24 ± 0.60 (27–36)	79.95 ± 1.00 (72–86)	29.76 ± 0.59 (26.7–35.4)

RH, Relative humidity; DBT, Dry-bulb temperature; THI, Temperature-humidity index.

3.3 Convective and conductive heat loss

On D35 heat loss recorded in the treatment groups was significantly higher ($p < 0.05$) compared to the control group. During the morning period of the study, the THI remained within the thermoneutral zone (TNZ) (Figure 1). However, at noon and in the evening, although the THI exceeded the TNZ, there was a significant difference ($p < 0.05$) in heat loss between the probiotic group and the control group (Figures 2, 3). On D21, all recorded heat loss values were within the TNZ, indicated by the yellow zone, for broiler chickens. However, on days 28 and 35 of the study, the heat loss values exceeded the TNZ, falling into the red zone (Figure 4).

4 Discussion

The elevated CT values observed in the control group suggest that these birds experienced a decreased ability to cope with thermal stress as they aged. The lack of any intervention in this group likely contributed to the higher CT, especially noticeable during the afternoon and evening hours. This observation is consistent with Egbuniwe et al. (26), who reported increased CT in chickens deprived of betaine and ascorbic acid, indicating that such deficiencies impair the birds' thermal regulation. In contrast, the probiotic-treated group exhibited significantly lower CT values, which can be attributed to the anti-stress properties of probiotic through its influence on the HPA axis. Yeast probiotics (*Saccharomyces cerevisiae*) have been shown to be effective anti-stress agents, improving broiler performance and heat tolerance when administered in appropriate doses during periods of thermal stress (6, 25). This finding supports Sugiharto et al. (33), who demonstrated that probiotics could modulate the adverse effects of increased metabolic heat production associated with higher body weight gains, thus enhancing heat dissipation in broilers. The lack of an additive effect on CT in the group receiving both probiotics and

TABLE 2 Changes in cloacal temperature of broiler chickens given probiotic and ascorbic acid.

Day	Time (h)	Group			
		Control	Probiotic	Ascorbic acid	Probiotic + AA
21	07:00	41.21 ± 0.27^{a}	39.98 ± 0.13^{b}	40.78 ± 0.11^{a}	41.04 ± 0.15^{a}
	09:00	40.35 ± 0.30^{a}	40.07 ± 0.20^{a}	40.46 ± 0.11^{a}	40.96 ± 0.08^{b}
	11:00	40.99 ± 0.25^{a}	40.72 ± 0.62^{a}	40.85 ± 0.09^{a}	41.06 ± 0.09^{a}
	13:00	41.00 ± 0.25^{a}	40.45 ± 0.08^{a}	40.80 ± 0.11^{a}	40.83 ± 0.12^{a}
	15:00	41.14 ± 0.20^{a}	40.84 ± 0.06^{a}	40.97 ± 0.04^{a}	40.98 ± 0.09^{a}
	17:00	41.53 ± 0.15^{a}	40.36 ± 0.10^{b}	41.11 ± 0.12^{a}	41.02 ± 0.08^{a}
	19:00	41.69 ± 0.18^{a}	40.84 ± 0.05^{b}	41.36 ± 0.14^{a}	41.20 ± 0.08^{a}
28	07:00	41.63 ± 0.15^{a}	39.80 ± 0.18^{c}	40.63 ± 0.14^{b}	40.52 ± 0.16^{b}
	09:00	41.39 ± 0.32^{a}	40.07 ± 0.20^{b}	40.46 ± 0.12^{b}	40.96 ± 0.08^{a}
	11:00	41.79 ± 0.22^{a}	40.78 ± 0.22^{b}	41.03 ± 0.22^{b}	41.01 ± 0.13^{b}
	13:00	41.69 ± 0.11^{a}	40.68 ± 0.13^{b}	40.78 ± 0.13^{b}	40.75 ± 0.12^{b}
	15:00	41.14 ± 0.20^{a}	40.84 ± 0.06^{a}	40.97 ± 0.06^{a}	40.98 ± 0.09^{a}
	17:00	41.71 ± 0.14^{a}	40.87 ± 0.16^{b}	41.03 ± 0.16^{b}	40.86 ± 0.14^{b}
	19:00	41.69 ± 0.17^{a}	41.10 ± 0.14^{a}	41.23 ± 0.14^{a}	41.07 ± 0.09^{a}
35	07:00	41.53 ± 0.20^{a}	40.36 ± 0.18^{b}	40.97 ± 0.15^{a}	41.01 ± 0.16^{a}
	09:00	41.15 ± 0.27^{a}	40.16 ± 0.18^{b}	40.49 ± 0.12^{b}	40.90 ± 0.14^{a}
	11:00	41.24 ± 0.24^{a}	40.86 ± 0.12^{a}	40.81 ± 0.11^{a}	41.02 ± 0.13^{a}
	13:00	41.47 ± 0.22^{a}	40.59 ± 0.13^{b}	40.89 ± 0.14^{b}	40.73 ± 0.12^{b}
	15:00	41.24 ± 0.20^{a}	40.81 ± 0.12^{a}	40.98 ± 0.11^{a}	40.86 ± 0.11^{a}
	17:00	41.49 ± 0.16^{a}	40.34 ± 0.12^{b}	41.09 ± 0.12^{a}	40.94 ± 0.11^{a}
	19:00	41.66 ± 0.17^{a}	40.94 ± 0.12^{b}	41.27 ± 0.13^{a}	40.98 ± 0.12^{b}

Mean values with different superscript letters along the same row are significantly different at $p < 0.05$. $n = 14$.

ascorbic acid may suggest that the mechanisms through which these two treatments operate are overlapping or synergistic in a way that does not result in enhanced benefits when combined during this study. Additionally, the physiological responses of the chickens to heat stress might have reached a maximum threshold, preventing any additional effects from the combined treatment. Despite ascorbic acid's role in reducing corticosterone levels through a negative feedback mechanism (15, 34), it did not demonstrate superior efficacy compared to the probiotic alone in mitigating thermal stress. This outcome suggests that while ascorbic acid can contribute to stress reduction, its impact may be limited by factors such as the specific dose used, the bioavailability of the antioxidant, or the inherent variability in the susceptibility of broiler chickens to these treatments. Additionally, it is worth considering that the efficacy of antioxidants can be influenced by their interaction with other components of the diet and environmental conditions (35). The varying responses observed in this study highlight the need for further research to optimize the use of these agents and understand their mechanisms in managing heat stress.

The lower temperatures recorded in the head, back, and feet of the treatment groups suggest that the probiotic and ascorbic acid played a significant role in enhancing the birds' ability to manage heat stress. During periods of heat stress, broiler chickens typically increase their oxygen intake to support thermoregulatory mechanisms such as evaporative cooling through panting (8, 36). This heightened oxygen consumption can lead to the accumulation of reactive oxygen species (ROS), which are byproducts of oxygen metabolism. When endogenous antioxidants are insufficient to counteract these ROS, oxidative stress can occur. The inclusion of exogenous antioxidants, such as *Saccharomyces cerevisiae* and ascorbic acid, may help neutralize these ROS, thereby reducing oxidative stress and supporting better thermal regulation (6, 15). The increased BST observed in the control group likely reflects the chickens' impaired ability to regulate heat, as indicated by their elevated CT. This supports the findings of Kim et al. (37), who noted that BST is a sensitive indicator of heat stress levels, with higher environmental temperatures leading to its increase. Although the study focused on laying hens, the relationship between environmental temperature, heat stress, and BST is also applicable to broiler chickens. The findings indicated that while the probiotic may help alleviate stress, combining it with ascorbic acid did not yield an additive effect on core temperature. This underscores the need for targeted approaches in broiler management. To optimize poultry welfare and performance during warmer months, practical recommendations for broiler producers are essential. These include incorporating probiotics into feeding regimens, monitoring environmental conditions, ensuring proper hydration, and adjusting brooding practices. By implementing these strategies, producers can enhance the resilience of their flocks and improve overall production outcomes in the face of climate-related challenges.

In the morning hours of the study, the THI was within the TNZ ideal for optimal broiler production. This favorable THI allowed for effective thermoregulation through convective and conductive heat

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TABLE 3 Variations in head, comb, wing, back and foot temperature of broiler chickens given probiotic and ascorbic acid.

Area	Day	Time (h)	Control	Treatment groups		
				Probiotic	Ascorbic acid	Probiotic + Ascorbic acid
	21	07:00	37.01 ± 0.53^{a}	36.79 ± 0.17^{a}	35.87 ± 0.15^{a}	33.00 ± 1.38^{b}
		13:00	36.03 ± 0.23^{a}	37.06 ± 0.23^{a}	34.00 ± 0.85^{b}	34.57 ± 0.91^{b}
		19:00	36.34 ± 0.18^{a}	37.16 ± 0.28^{a}	35.69 ± 0.48^{b}	32.34 ± 0.68^{c}
	28	07:00	37.10 ± 0.43^{a}	36.26 ± 0.19^{a}	35.83 ± 0.21^{a}	32.59 ± 1.49^{b}
		13:00	35.91 ± 0.25^{a}	36.89 ± 0.25^{a}	35.09 ± 0.23^{a}	35.07 ± 0.73^{a}
		19:00	37.89 ± 0.62^{a}	37.00 ± 0.21^{a}	38.20 ± 0.60^{a}	36.06 ± 0.41^{b}
	35	07:00	37.17 ± 0.42^{a}	36.67 ± 0.17^{a}	35.93 ± 0.22^{a}	36.16 ± 0.86^{a}
		13:00	36.79 ± 0.49^{a}	36.91 ± 0.28^{a}	36.17 ± 0.32^{a}	35.97 ± 0.51^{a}
Head		19:00	37.49 ± 0.41^{a}	35.84 ± 0.50^{b}	35.69 ± 0.65^{b}	35.20 ± 0.29^{b}
	21	07:00	36.63 ± 0.42^{a}	35.97 ± 0.20^{a}	35.51 ± 0.11^{a}	35.21 ± 1.51^{a}
		13:00	35.86 ± 0.16^{a}	36.21 ± 0.07^{a}	33.19 ± 0.58^{b}	33.50 ± 0.81^{b}
		19:00	36.96 ± 0.25^{a}	36.53 ± 0.10^{a}	37.73 ± 0.44^{a}	36.00 ± 0.69^{a}
	28	07:00	36.37 ± 0.36^{a}	36.76 ± 0.48^{a}	35.59 ± 0.18^{a}	36.30 ± 0.17^{a}
		13:00	35.74 ± 0.18^{a}	36.24 ± 0.21^{a}	35.19 ± 0.50^{a}	35.64 ± 0.38^{a}
		19:00	35.60 ± 0.47^{a}	36.41 ± 0.11^{a}	37.73 ± 0.48^{b}	36.14 ± 0.48^{a}
	35	07:00	35.27 ± 0.42^{a}	37.59 ± 0.58^{b}	36.23 ± 0.26^{a}	37.14 ± 0.41^{b}
		13:00	34.53 ± 0.49^{a}	36.50 ± 0.33^{b}	35.90 ± 0.23^{a}	36.43 ± 0.41^{b}
Comb		19:00	35.93 ± 0.42^{a}	37.96 ± 0.67^{b}	37.53 ± 0.41^{b}	36.57 ± 0.54^{a}
	21	07:00	36.23 ± 0.34^{a}	39.16 ± 0.27^{b}	40.47 ± 0.32^{c}	37.23 ± 0.50^{a}
		13:00	39.83 ± 0.20^{a}	39.23 ± 0.46^{a}	39.01 ± 0.50^{a}	38.44 ± 0.33^{a}
		19:00	39.83 ± 0.20^{a}	40.07 ± 0.13^{b}	39.90 ± 0.35^{a}	38.30 ± 0.07^{a}
	28	07:00	35.76 ± 0.16^{a}	39.07 ± 0.29^{c}	40.09 ± 0.26^{c}	37.39 ± 0.48^{b}
		13:00	39.83 ± 0.48^{a}	40.54 ± 0.40^{a}	39.30 ± 0.72^{a}	40.44 ± 0.47^{a}
		19:00	37.87 ± 0.84^{a}	40.34 ± 0.26^{b}	40.59 ± 0.34^{b}	39.73 ± 0.68^{b}
	35	07:00	35.71 ± 0.36^{a}	39.30 ± 0.30^{c}	40.40 ± 0.28^{c}	37.53 ± 0.43^{b}
		13:00	36.81 ± 0.73^{a}	39.14 ± 0.45^{b}	38.90 ± 0.49^{b}	37.87 ± 0.65^{b}
Wing		19:00	37.81 ± 1.09^{a}	40.10 ± 0.13^{b}	39.71 ± 0.31^{b}	38.86 ± 0.30^{b}

(Continued)

TABLE 3 (Continued)

Area	Day	Time (h)	Control	Treatment groups		
				Probiotic	Ascorbic acid	Probiotic + Ascorbic acid
	21	07:00	37.43 ± 0.59[a]	36.06 ± 0.23[a]	36.96 ± 0.38[a]	31.81 ± 0.84[b]
		13:00	36.36 ± 0.11[a]	36.61 ± 0.28[a]	36.69 ± 0.91[a]	34.89 ± 0.62[a]
		19:00	37.36 ± 0.11[a]	34.26 ± 0.33[c]	36.66 ± 0.88[b]	35.50 ± 0.69[b]
	28	07:00	36.87 ± 0.78[a]	35.83 ± 0.25[a]	36.67 ± 0.45[a]	35.61 ± 0.68[a]
		13:00	36.37 ± 0.13[a]	36.53 ± 0.18[a]	37.27 ± 0.85[a]	35.57 ± 0.36[a]
		19:00	39.96 ± 0.97[a]	37.16 ± 0.35[b]	38.69 ± 0.95[a]	36.07 ± 0.37[c]
	35	07:00	37.36 ± 0.67[a]	36.01 ± 0.26[a]	36.89 ± 0.38[a]	36.39 ± 0.88[a]
		13:00	37.56 ± 0.62[a]	36.04 ± 0.30[b]	36.06 ± 0.81[b]	35.60 ± 0.40[b]
Back		19:00	38.31 ± 0.13[a]	36.04 ± 0.36[b]	37.46 ± 0.82[b]	35.64 ± 0.21[c]
	21	07:00	36.74 ± 0.57[a]	35.94 ± 0.18[a]	36.34 ± 0.25[a]	36.06 ± 0.19[a]
		13:00	35.39 ± 0.17[a]	35.50 ± 0.24[a]	34.16 ± 1.04[a]	35.34 ± 1.14[a]
		19:00	38.30 ± 0.16[a]	37.57 ± 0.36[a]	37.33 ± 0.19[a]	35.09 ± 1.60[b]
	28	07:00	36.70 ± 0.51[a]	35.89 ± 0.18[a]	36.24 ± 0.24[a]	35.94 ± 0.22[a]
		13:00	35.50 ± 0.20[a]	35.47 ± 0.21[a]	34.01 ± 0.98[b]	34.36 ± 0.95[b]
		19:00	39.16 ± 1.02[a]	37.57 ± 0.36[b]	38.33 ± 0.19[a]	35.66 ± 1.27[c]
	35	07:00	36.67 ± 0.59[a]	35.86 ± 0.19[b]	36.27 ± 0.23[a]	36.03 ± 0.25[a]
		13:00	35.71 ± 0.22[a]	35.26 ± 0.29[a]	34.41 ± 0.83[b]	36.06 ± 0.80[a]
Foot		19:00	37.50 ± 0.66[a]	37.29 ± 0.36[a]	37.59 ± 0.59[a]	36.46 ± 1.08[a]

Mean values with different superscript letters along the same row are significantly different at $p < 0.05$. $n = 14$.

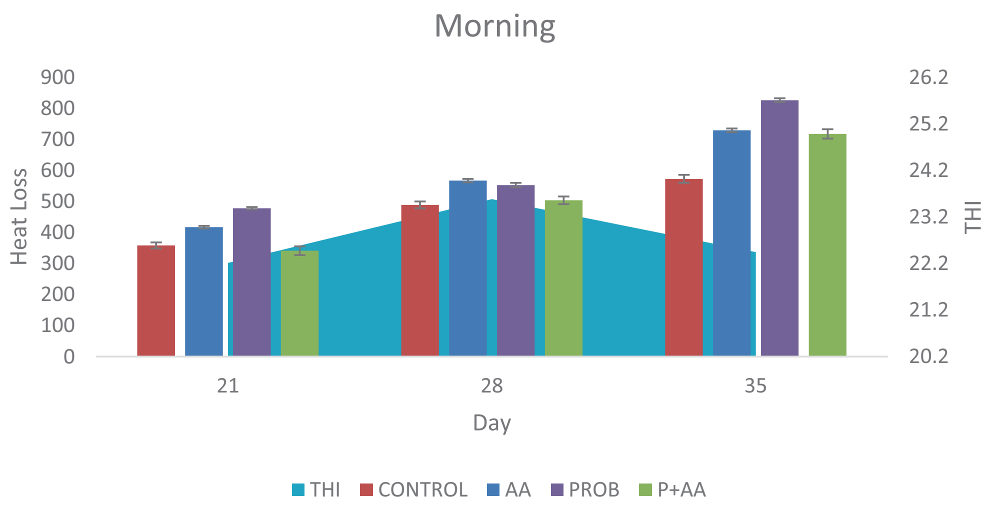

FIGURE 1
Convective and conductive heat loss obtained during the morning hours of the study period. The THI was within the TNZ stipulated for broiler chickens which influenced the degree of heat loss positively during this period of the study (*n* = 7). THI; temperature-humidity index, TNZ; thermoneutral zone.

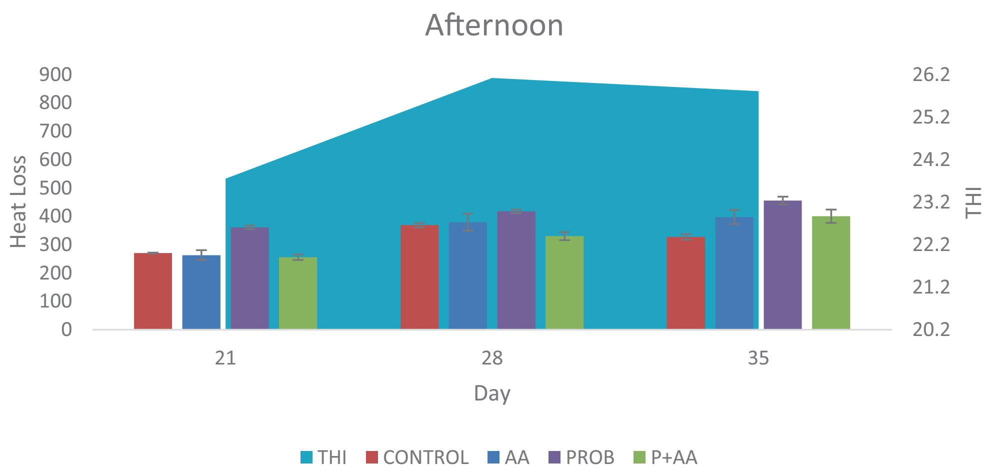

FIGURE 2
Convective and conductive heat loss obtained during the afternoon hours of the study period. The THI exceeded the TNZ for broiler chickens which influenced the degree of heat loss negatively during this period of the study (*n* = 7). THI, temperature-humidity index; TNZ, thermoneutral zone.

loss, which was evident in the treatment groups as THI is the descriptive indicator of heat stress [(38); Xinyao et al., 2022]. Throughout the study, broiler chickens accumulated heat from both environmental sources and metabolic processes. However, the primary focus was on assessing sensible heat loss in the treatment and control groups. It is important to acknowledge that while the antioxidants contributed to increased heat loss, the overall effectiveness of heat dissipation was also influenced by the THI. Variations in THI during different periods of the study likely impacted the heat loss dynamics. Tao and Xin (39), found that the optimal THI for broiler production is around 21, suggesting that maintaining THI within this range is crucial for minimizing heat stress and ensuring optimal performance. This implies that alongside antioxidant supplementation, managing THI effectively is essential for enhancing broiler welfare and productivity. During the afternoon and evening hours of the study, the THI exceeded the TNZ optimal for broiler chickens' production. Such conditions are expected to reduce heat loss through conduction and convection. Despite this, the probiotic group demonstrated a higher degree of heat loss compared to the control group on D21 and D35. This increased heat loss in the probiotic group can be attributed to the antistress effect of this agent. These findings align with the research of Sinkalu et al. (40) and Aluwong et al. (6), who both identified that THI levels above 21 induce heat stress in broiler chickens. Their studies utilized CT as a biomarker to assess heat stress, corroborating the observation that high THI contributes to increased heat stress.

The TNZ is the optimal temperature range in which broiler chickens can maintain their physiological functions without needing to expend extra energy for thermoregulation (8). This zone, also known as the comfort zone, is crucial for achieving peak performance

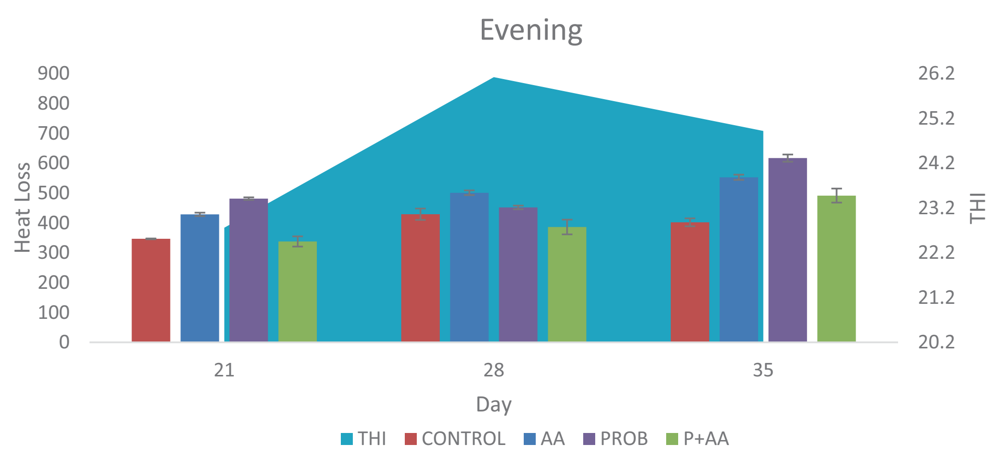

FIGURE 3
Convective and conductive heat loss obtained during the evening hours of the study period. The probiotic and ascorbic acid groups had a significantly higher ($p < 0.05$) value of heat loss when compared with the control group on D21 and D35. The THI was outside the TNZ stipulated for broiler chickens which negatively influenced the degree of heat loss during this period of the study ($n = 7$). THI, temperature-humidity index; TNZ, thermoneutral zone.

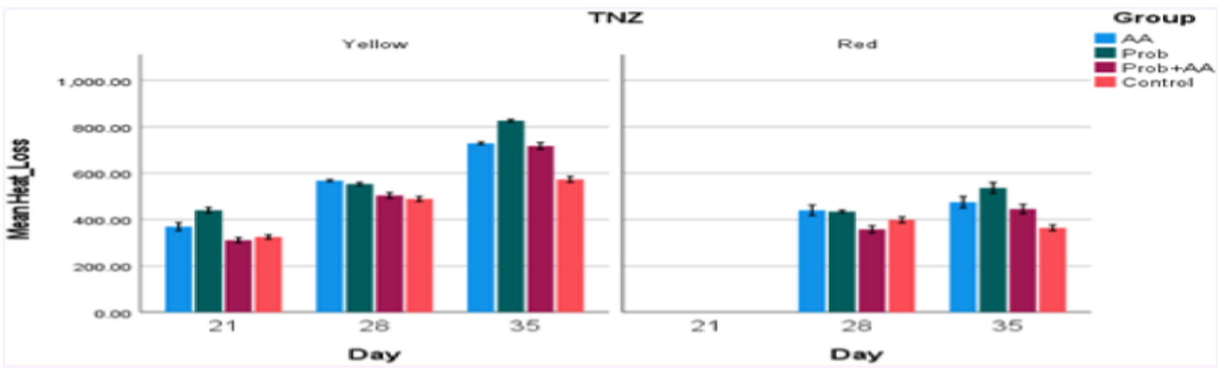

FIGURE 4
Convective and conductive heat loss within (yellow zone) and outside (red zone) the TNZ in broiler chickens treated with probiotic and ascorbic acid. At D21, heat loss values obtained were within the TNZ, while those recorded on D28 and D35 surpassed the TNZ stipulated for broiler chickens during the afternoon and evening periods of the study ($n = 7$).

and welfare in broiler chickens (13). Within this range, known as the zone of comfort (yellow zone), the broilers can effectively manage their body temperature and perform optimally. However, when ambient temperatures exceed this range, entering the zone of discomfort (red zone), the chickens experience increased stress and reduced performance (39). During the study, THI values recorded on D21 and in the morning hours of D28 and D35 remained within the TNZ. These favorable conditions facilitated effective thermoregulation in the broiler chickens, as evidenced by efficient heat loss through convection and conduction. The ability to maintain normal physiological functions and comfort levels was thus supported. In contrast, the THI values recorded during the afternoon and evening hours of D28 and D35 were above the TNZ, which significantly impaired the chickens' ability to regulate their body temperature. This was reflected in the reduced effectiveness of heat dissipation mechanisms, leading to compromised welfare and performance (26). The elevated temperatures in these periods resulted in increased physiological stress and diminished comfort for the broilers. Our study indicates that higher AT beyond the TNZ negatively affects the thermoregulatory processes in broiler chickens, particularly when no anti-stress interventions are applied. The data suggest that as AT increased and exceeded the TNZ, the capacity for effective thermoregulation diminishes, highlighting the critical need for environmental management and stress mitigation strategies. This reinforces the importance of maintaining environmental conditions within the TNZ to optimize broiler health and productivity (10, 44). Additionally, the findings underscore the potential benefits of implementing anti-stress measures, such as dietary supplements like probiotics (*Saccharomyces cerevisiae*) and ascorbic acid to support broiler welfare during periods of thermal stress. Further research should explore the interaction between various antioxidant types and environmental conditions to develop comprehensive strategies for managing heat stress in broiler production. This could include optimizing antioxidant dosages and combining them with environmental controls to achieve the best outcomes for broiler health and performance. Understanding how fluctuations in THI influence heat stress and performance at different growth phases can inform more targeted management practices. Also, the effects of different combinations and dosages of antioxidants, including probiotics and ascorbic acid should be studied, to determine their synergistic potential in mitigating heat stress.

5 Conclusion

The study highlights the importance of maintaining ambient temperatures within the TNZ to optimize the welfare and performance of broiler chickens. It found that when THI values are within the TNZ, chickens effectively regulate their body temperature, but exceedance leads to impaired thermoregulation, elevated CT, and increased heat stress. Practical recommendations for producers include supplementing feed with probiotics, which have been effective in reducing heat stress effects, as opposed to ascorbic acid, which has a less pronounced impact during this study. Producers should, therefore, integrate probiotics into their feeding strategies, especially during warmer months. Future research should aim to optimize dosages and combinations of probiotics and ascorbic acid, explore their specific mechanisms, and assess long-term effects on health and productivity. Overall, maintaining temperatures within the TNZ and implementing these anti-stress interventions can enhance broiler resilience and improve production outcomes.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

The animal study was approved by the University of Pretoria Animal Ethics Committee (REC050-20). The study was conducted in accordance with the local legislation and institutional requirements.

Author contributions

VS: Conceptualization, Data curation, Funding acquisition, Investigation, Methodology, Project administration, Resources, Validation, Visualization, Writing – original draft, Writing – review & editing. VN: Data curation, Formal analysis, Funding acquisition, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – review & editing. MO: Funding acquisition, Project administration, Resources, Supervision, Validation, Visualization, Writing – review & editing. JC: Conceptualization, Data curation, Funding acquisition, Investigation, Project administration, Resources, Supervision, Validation, Visualization, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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Climate change impact on blood haemogram in the horse: a three-year preliminary study

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Introduction: The global climatic changes pose a substantial threat to the well-being and productivity of both humans and animals.

Methods: This study examined the impact of climate changes during different seasons over a 3-year monitoring period (2021–2023) on various blood parameters including, white blood cells (WBC), neutrophils, basophils, eosinophils, lymphocytes, and monocytes, hematocrit (HCT), hemoglobin (HGB), red blood cells (RBC), platelets (PLT), mean corpuscular hemoglobin concentration (MCHC), mean corpuscular volume (MCV), and mean corpuscular hemoglobin (MCH). The study focused on 25 Thoroughbred mares located in Kastamonu-Türkiye. Thermal and hygrometric parameters, including ambient temperature, relative humidity, and ventilation, were collected. Subsequently, Temperature-Humidity index (THI) was computed. Blood samples were collected on the first day of every month from January 2021 to December 2023 and used for a complete blood count analysis. Between 2021 and 2023, changes in environmental indicators were correlated to changes in hematological parameters.

Results: Two-way for repeated measures ANOVA revealed a significant seasonal fluctuation (<0.0001) in ambient temperature, relative humidity, and THI. There was a reduction in RBC (<0.01), and MCH (<0.01) every year, HGB (<0.0001) in summer 2021, 2022 and in summer and autumn 2023. HCT (<0.0001), MCV (<0.01), showed decreasing values in autumn 2022 and 2023. MCHC values showed increasing values in July and August 2021, 2022 and in June 2023. WBC levels increased throughout the spring periods of 2021 and 2022. In April 2021, there were elevated levels of lymphocytes and monocytes (<0.0001) respectively.

Discussion: These findings could be helpful to promote the monitoring of physiological status both for the assessment of welfare status and for diagnostic purposes for the evaluation of possible disease outbreaks due to climate change in veterinary medicine.

KEYWORDS

horses, climate changes, haemogram, seasonal variations, hematology

1 Introduction

Currently, global temperature trends and weather conditions are showing long-term deviations from historical seasonal average values and temperatures are predicted to continue to rise steeply in the coming decades (1). Seasonal variability in temperature, humidity, wind and rainfall, has been today classified as a potential risk to human welfare, animal growth and production (2). In fact, climate change is widely recognized as one of the most significant challenges facing the planet, for both humans and animals (3). Climate change and global warming is responsible for a higher frequency of extreme weather events and changing conditions, such as intense rainfall, frost, prolonged heat cycles, and prolonged drought (4–6). These effects negatively influence the viability, sustainability, productivity and reproduction of animal species, as well as compromising sports performance in horses (7). Direct effects of climate change resulting from increased greenhouse gasses such as carbon dioxide (CO2) concentrations influence mammalian thermoregulation, metabolism, immune system function and production (8–10). Indirect effects negatively influence feed production, water availability and parasite/pathogen populations (11, 12).

It was previously shown that severe weather events negatively affect the training and transport of athletic horses (13–17). Further literature suggested that climate change is increasing the risk of some diseases in domestic animals through increasing abundance of wildlife vectors and reservoirs, the survival of pathogens in the environment and husbandry practices (18). Horses are increasingly affected by respiratory diseases caused by smoke and dust from wildfires, skin diseases, hoof damage, parasites and emerging diseases, as a result of weather variability. In addition, drier and warmer conditions have been associated with an increase in bacterial infections associated with fecal contamination of dry soils (19).

Many implications of climate change may be observed and preliminarily recognized through changes in the hematological profile of animals. The influence of seasonal variations on hematological parameters has been largely studied in dairy cows (20–22), sheep (23), goats (24) and horses (9, 25, 26). Blood is a very dynamic tissue and its primary responsibility is the maintenance of body homeostasis in various conditions (25, 27). Hematological analysis is essential for monitoring general health conditions of individuals, to confirm clinical diagnoses and to monitor disease evolution and recovery during treatments (28–30).

In athletic horses, it serves as an optimal indicator to assess performance and to evaluate an animal's physiological adaptability to exercise and to adverse environmental conditions (26–32). In domestic animals, hematological parameters depend on several factors including age, sex, breeds, diet, exercise, reproductive status, housing system and microclimatic conditions (25, 33–38). The knowledge of hematological physiology is an important tool that can be used as an effective and sensitive index to monitor physiological and pathological conditions in horses (39).

Hematological parameters are subject to periodic variations associated with biological rhythms in a number of species, including humans and horses (25, 40–43). Oscillations of biological functions, sustained with a period of about 1 day, are called circadian rhythms. Other endogenously generated biological rhythms include circatrigintan rhythms (with a period of about a month) and circannual rhythms (with a period of about 1 year) (13, 44).

All biological rhythms reflect the ability of endogenous adaptative mechanisms of animals to react in advance to environmental changes associated with daily and seasonal environmental changes (9, 39). Seasonality has an impact on several biological and physiological mechanisms in domestic animals based on periodic changes of photoperiod, nutritional availability, relative humidity and temperature that regulate changes in reproductive activity, pelage, lactation and metabolism (43, 45–48). The evaluation and analysis of seasonal changes in physiological parameters helps develop a better understanding of the effects of thermal changes on physiology and associated adaptation/acclimatization in mammals (49).

The objective of this study was to evaluate the possible variation in the hematological profile of horses in relation to seasonal climatic changes over a three-year period. This could potentially offer a picture of how changing environmental exposures associated with climate change and season impact important physiological parameters that can have an influence on welfare, diagnosis and performance.

2 Materials and methods

This study was approved by Kastamonu University Animal Experiments Local Ethics Committee and an approval certificate (Decision no: 2024/24) was obtained.

The data obtained during the monthly health status check of a regional breeding farm in Kastamonu city, Turkey, were used to conduct this retrospective study. Twenty-five healthy, non-pregnant retired Thoroughbred mares aged between 9 and 20 years old and with a mean body weight of 558 ± 20 kg were randomly chosen to be enrolled in the study. The mares were housed in individual stables, each measuring between 6 and 12 square meters. They were turned out to adjacent paddocks for a number of hours depending on seasons and weather conditions and were managed by experienced stable staff. Mares were located at Golkoy Breeding Farm 1 in Kastamonu-Turkey (Latitude: 41.371; Longitude: 33.7756; Altitude: 800.0 m). Prior to the start of the study, each horse underwent physical examination to establish health status (body temperature, heart rate, respiratory rate). During the experimental period the horses in the study had regular health checks from the same veterinarian, thus, none of the study horses were replaced or got sick. Routine deworming and vaccinations were delivered at weeks apart from the blood sampling, to avoid any confounding effects on the blood parameters caused by immune activation.

Mares were fed twice a day at 06:00 and 18:00 with good quality hay and concentrates: 44% oatmeal (2.64 kg), 24% crushed barley (1.44 kg), 12% maize (0.72 kg), 15% soybean meal (0.9 kg), 4% bran (0.24 kg), salt, concentrated pellet feed (6 kg), dry grass (5 kg), lucerne (4 kg) and one mineral block. Water intake was available *ad libitum*. Thermal and hygrometric parameters (ambient temperature- °C; relative humidity- %; and ventilation- m/s) were obtained through access to the Kastamonu Meteorology Directorate to evaluate microclimatic conditions.

The temperature-humidity index (THI) was calculated according to the formula reported in Thom (70):

THI = [0.8 × T + (RH/100) × (T − 14.4) + 46.4] where T is the average ambient temperature expressed in °C and RH is the relative humidity expressed in % (50, 51).

2.1 Blood sampling and analysis

Blood samples were collected via jugular venipuncture into 4 mL vacutainer tubes containing EDTA-3K before the morning feeding (05:30) every first day of each month from January 2021 to December 2023. All blood samples were refrigerated at 4°C and analyzed for complete blood count (CBC) within 2 h. White blood cells (WBC), neutrophils, basophils, eosinophils, lymphocytes, and monocytes, hematocrit (HCT), hemoglobin concentration (HGB), red blood cells (RBC), platelets (PLT), mean corpuscular hemoglobin concentration (MCHC), mean corpuscular volume (MCV), mean corpuscular hemoglobin (MCH), were measured and counted using an automated hematology analyzer [HASVET VH5R Antalya, Türkiye (Norma iVet-5 device manufactured by Norma Diagnostika Budapest, Hungary)].

2.2 Statistical analysis

Normal distribution of the data was tested using Kolmogorov–Smirnov tests. Differences in hematological and environmental parameters for the independent variables of month and year were investigated using two-way repeated measures analysis of variance (ANOVA) followed by *post hoc* multiple comparison tests where appropriate. Percentage changes between study years in environmental and hematological parameters were calculated using Microsoft Excel 2021. Monthly values were first grouped by season (Dec, Jan, Feb = winter; Mar, Apr, May = spring; Jun, Jul, Aug = summer; and Sep, Oct, Nov = autumn) and mean values calculated. Regression lines between the monthly values of each hematological parameter and, 95% confidence interval for monthly mean max ambient temperature, chosen as a representative value, and relative humidity for all years were determined and Pearson correlation coefficient (r) was evaluated. Data were analyzed using statistical software Graph Pad Prism v. 9.5.1 (Graphpad Software Ltd., United States). Data were reported as means ± standard deviation (SD), a p-value less than 0.05 was considered statistically significant and q-value corresponding to the adjusted p-value (False Discovery Rate) was determined.

3 Results

Data were not normally distributed ($p < 0.05$). The values for all hematological parameters were within the reference ranges of horses for the entire monitoring period (52). The two-way ANOVA was performed to analyze the effect of month and year on hematological and environmental parameters. A significant effect of month was observed for ambient temperature ($p < 0.0001$; q=), relative humidity and THI showed a significant effect of month ($p < 0.0001$). Multiple comparison of environmental parameters was reported in Table 1. No significant variation of month and year was observed for ventilation. The application of two-way ANOVA on the hematological parameters revealed a significant effect of month on WBC (<0.01), Neutrophils (Neutr) (<0.0001), Lymphocytes (Lymph) (<0.0001), Monocytes (Mon) (<0.0001), RBC (<0.01), HGB (<0.0001), HCT (<0.0001), MCV (<0.01), MCH (<0.01) and MCHC (<0.0001) and a significant effect of year on WBC (<0.01), Neutr (<0.01), Lymph (<0.0001), Mon (<0.0001), RBC (<0.01), HGB (<0.01), HCT (<0.0001), MCV (<0.01), MCH (<0.0001) and MCHC (<0.0001) as shown in Figures 1, 2. The percentage change of hematological parameters observed during the 3 years is shown in Table 2. A positive correlation was observed between monthly mean max ambient temperature and Neutr ($p < 0.01$: $r = 0.45$), and between relative humidity and Lymph ($p < 0.01$; $r = 0.38$), RBC ($p < 0.01$; $r = 0.39$), HGB ($p < 0.01$; $r = 0.43$) and HCT ($p < 0.001$; $r = 0.48$). A negative correlation was observed between monthly mean max ambient temperature and Lymph ($p < 0.01$; −0.33), RBC ($p < 0.01$; $r = -0.35$), HGB ($p < 0.01$; $r = -0.37$), HCT ($p < 0.001$; $r = -0.48$) and between relative humidity and Neutr ($p < 0.001$; $r = -0.53$) (Figure 3).

4 Discussion

Many areas are facing increasing pressure from the effects of climate change, such as rising temperatures, increased variability in rainfall, increased frequency of extreme events and increased carbon dioxide concentrations. These changes have been found to impact domestic animal performance, production and welfare (11). Referring to the impact of microclimate, ambient temperature is an important ecological physical and environmental stimulus (53). Extreme hot and cold ambient temperatures affect animals physiological adaptation responses (54). The THI was used to estimate the degree of thermal stress experienced by an animal (51). It can be categorized into mild (70–80), severe (80–85), and deadly stress zones (>85), reflecting environmental conditions (9). The present ambient temperature and THI recorded were within the thermoneutral zone for horses, thus external conditions were all considered comfortable for horses during the experimental period (9). The present results showed no significant variations between all environmental parameters over the 3 years monitored. According to Table 1, summer and autumn periods resulted in higher average ambient temperature compared to winter and spring. Previous studies observed that seasonal variations may affect hematological profile and welfare in horses (21, 22, 25, 32). During 2021 RBC values decreased in August and September. During 2022, significantly lower values were observed in June, July, September, October and November, and during 2023 in August, September and November compared to other months. HGB decreased in July, August and September 2021, during 2022 minimum HGB values were observed in April, June, October and November and in April, May, June, July, August, September and November 2023. HCT values showed a decrease in autumn months (September, October, and

TABLE 1 Three year data for maximum, average and minimum values of ambient temperature and ventilation, relative humidity percentage and THI obtained from 2021 to 2023 across the four seasons, expressed in their conventional units.

Experimental conditions	Winter			Spring			Summer			Autumn		
	December	January	February	March	April	May	June	July	August	September	October	November
2021												
Ambient temperature (°C)												
max	15^{pqrs}	16^{pqrs}	17^{pqrs}	18^{pq}	27	32	29	39^{ar}	37^{ar}	27^{r}	22	22
avg	1^{pqrs}	1^{pqrs}	2.25^{pqrs}	7^{pqrs}	13.75^{pq}	14.75^{qr}	19.5^{r}	19.75^{r}	14.5^{r}	9.75^{r}	6.5	2
min	-14	−15^{pqrs}	−17^{pqrs}	−8^{pqrs}	−4^{q}	−2^{q}	4^{r}	9^{r}	9^{r}	3	−2	−5
Relative humidity (%)	82^{pqrst}	80^{pqrs}	79^{pqrs}	75^{pqrs}	70^{q}	70^{qr}	67	62^{r}	59^{r}	62^{r}	68	72
Ventilation (m/s)												
max	13.1	12.4	10.7	11.1	10.9	13.1	11.7	11.3	10.6	10.9	11.3	11.5
avg	6.31	6.55	6.51	6.98	6.8	5.63	7.11	6.12	6.37	4.71	4.59	5.84
min	2.6	1.6	3.4	4	3.2	2.7	4.7	3.9	2.2	2.7	1.6	3.3
Temperature-humidity index (THI)	36.21^{pqrs}	34.6^{pqrs}	38.60^{pqrs}	46.45^{pq}	56.94^{pq}	58.55^{qr}	67.1^{r}	65.51^{r}	58.06^{r}	51.32^{r}	46.23	39.07
2022												
Ambient temperature (°C)												
max	16^{pqrs}	12^{pqrs}	17^{pqrs}	18^{pq}	29	31	30	33^{ar}	34^{ar}	34^{r}	28	20
avg	4^{pqrs}	−1.5^{pqrs}	0.75^{pqrs}	0^{pqrs}	9.25^{pq}	12.25^{qr}	16.75^{r}	18.75^{r}	22.5^{r}	16.5^{r}	11	7.25
min	−4	−14^{pqrs}	−11^{pqrs}	−14^{pqrs}	−2^{q}	1^{q}	8^{r}	6^{r}	12^{r}	1	−2	−2
Relative humidity (%)	82^{pqrst}	80^{pqrs}	79^{pqrs}	75^{pqrs}	70.51^{q}	70.46^{qr}	68.69^{qr}	62^{r}	59^{r}	62^{r}	68.1	75
Ventilation (m/s)												
max	7.6	12.3	8.5	11.7	13.8	10.5	10.2	9.1	8.8	8.5	9.5	10
avg	4.29	6.45	5.42	7.01	7.51	6.1	6.57	6.76	5.15	5.84	5.43	4.94
min	1.6	2.2	2.8	3.6	3.6	3.6	3.2	4.6	2.4	3.5	2.1	2.4
Temperature-humidity index (THI)	41.07^{pqrs}	32.48^{pqrs}	36.22^{pqrs}	46.4^{pqrs}	50.17^{q}	54.68^{qr}	62.15^{r}	65.75^{r}	69.09^{r}	60.90^{r}	52.88	47.14
2023												
Ambient temperature (°C)												
max	16^{pqrs}	13^{pqrs}	16^{pqrs}	19^{pq}	22	24	29	34^{ar}	39^{ar}	32^{r}	26	24
avg	3.5^{pqrs}	1.75^{pqrs}	0.75^{pqrs}	4.5^{pqrs}	8.5^{pq}	11.5^{qr}	16.5^{r}	19.75^{r}	22.25^{r}	18.75^{r}	12	6.75
min	−7	−7	−10	−10	−1	−1	7	8	10	4	0	−7

(Continued)

TABLE 1 (Continued)

Experimental conditions	Winter			Spring			Summer			Autumn		
	December	January	February	March	April	May	June	July	August	September	October	November
Relative humidity (%)	82.13^{pqrst}	81^{pqrst}	79^{pqrst}	75^{pqrst}	71^{q}	70.36^{qr}	68.73^{qr}	63^{r}	59^{r}	62^{r}	68	76
Ventilation (m/s)												
max	11.3	9.9	13.4	11.5	11.4	10.9	7.6	11.7	9	8.9	10.7	22
avg	3.92	4.03	7.89	6.23	6.61	4.5	4.88	6.39	6.86	6.53	5.62	9.3
min	2.6	1.5	2	2.1	3.9	2	1.9	2.7	3.6	3.5	3.5	2.8
Temperature-humidity index (THI)	40.26^{pqrs}	37.55^{pqrs}	36.22^{pqrs}	42.57^{pqrs}	49.1^{q}	53.57^{qr}	61.05^{r}	65.57^{r}	68.83^{r}	64.09^{r}	54.37	45.99

Superscript letters denote significance of Bonferroni *post hoc* tests: ^{p} vs. May and June, ^{q} vs. July, August and September, ^{r} vs. October and November, ^{s} vs. April, ^{t} vs. February and March.

November) compared to winter (December, January, and February) and spring (March, April, and May) 2022 and 2023.

The present findings were in agreement with previous studies in horses (9, 39, 55, 56), sheep (57), cows (58, 59) and goats (45, 60). Values of MCV measured in 2021 and 2022 showed lower values during July and August and in October during 2023. MCH values showed a statistical decrease in July and August during 2021 and an increase in June and July during 2022. The MCV and MCH was observed to have lower values during summer as also observed in previous studies in horses (25) and donkeys (32), suggesting that this adaptation could be related to reduction in cellular oxygen requirements in order to reduce metabolic heat load (61). MCHC values showed increased values in July and August during 2021, 2022 and in June during 2023. These variations were previously considered as metabolic acclimation to the environmental conditions (26). Reduced temperatures during winter are related to increased sympathetic activity by increasing metabolic capacity and inducing mobilization of the spleen to release erythrocytes into the bloodstream by promoting erythropoiesis (62, 63). Enhanced sympathetic activity in winter could lead to increased spleen mobilization, with the release of blood into the bloodstream (63). Higher ambient temperature stimulated an hemodilution effect, in which water was diverted into the circulatory system for evaporative cooling in association with the thermoregulatory mechanism, which influences RBC, HGB and HCT concentration (31).

White blood cell values showed increasing values in April and March during 2021 and 2022. Similarly, Lymph and Mon show high values in April during 2021 and during 2023 for Mon confirming previous studies (49, 58). Stress associated with cold weather in winter may suppress the immune response (64). The overall increase in WBC during spring was related to an increase in lymphocytes, monocytes, neutrophils and eosinophils, likely caused by increased infestation and bites from pests and insects (65).

A significant effect of the year was observed for the studied parameters. Red blood cells showed an increase in February from 2021 to 2023. A decrease in RBC values during spring (March, April, and May) 2022–2023 of 8.96% and from spring 2021 to 2023 of 7.35% was observed according to Table 2. Hemoglobin showed an increase in February 2022 and 2023 compared to 2021 and an increase in December and March 2022. A decrease in HGB was observed in March, July, August, and November 2023 compared to 2022 and a decrease in April 2023 compared to 2021. Hematocrit values in 2022 increased in February and March and decreased in October compared to 2021. In 2023 compared to 2021, HCT values increased in February and decreased in April, July, September, and November and decreased in March and April compared to 2022. MCV showed an increase in February, April, May, and September 2022 compared to 2021. A 6.75% increasing of MCH was shown in October and December 2022 compared to 2021 and in summer (June, July, and August). A statistical increase in MCH values in winter (December, January, and February) by 6.26%, spring (March, April, and May) by 5.92%, and summer (June, July, and August) by 5.42% was observed in 2023 compared to 2021. In 2023 compared to 2022, an increase was observed in January and February and during spring by 1%. In 2022, MCHC showed a decrease in January and February, a decrease of 3.69% during spring and an increase in June, July and

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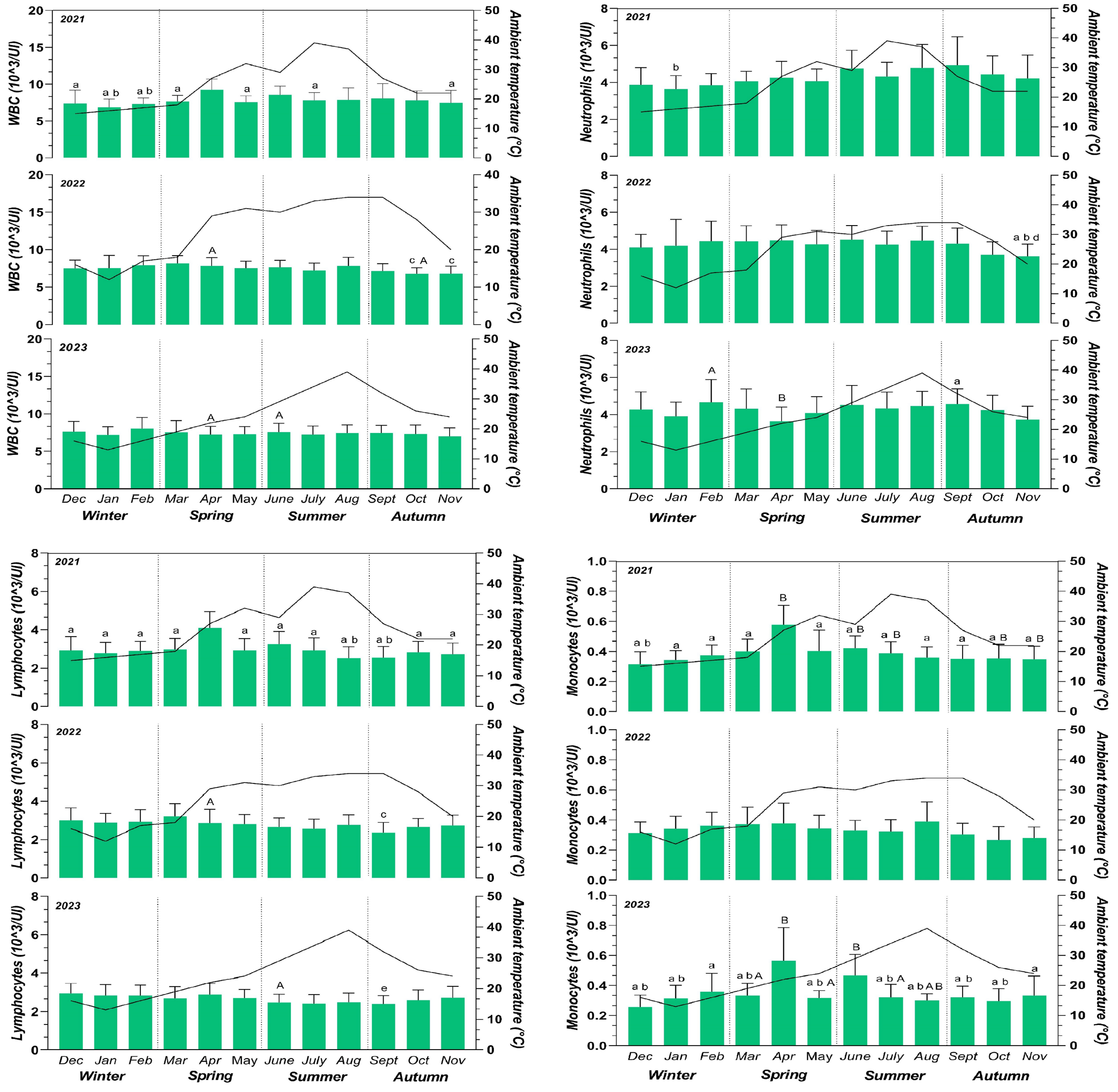

FIGURE 1
Mean values ± standard deviation (±SD) of WBC, neutrophils, lymphocytes and monocytes obtained from a monthly monitoring of 25 horses during a 3-year (2021–2023) period considering the four seasons with monthly fluctuations of the max ambient temperature during the monitoring period. Significances among months (p < 0.05): ^{a} vs. April; ^{b} vs. June, ^{c} vs. March, ^{d} vs. August and ^{e} vs. December significances among years (p < 0.05): ^{A} vs. 2021; ^{B} vs. 2022.

September compared with 2021. In 2023, an increase in January, February and July and a percentage increase of 7.82% was observed during spring compared to 2021. A percentage increase of 3.83 and 6.44% was observed in 2023 during spring and autumn respectively, compared to 2021. A significant increase in MCHC was observed in 2023 during January, February, June and July compared to 2021. White blood cells showed decreasing values in April and October during 2022 compared to 2021 and decreasing values in April and June during 2023 compared to 2021. Lymphocytes showed decreasing values in April during 2022 and in June during 2023 compared to 2021. In 2023 increasing values were observed for Neutr in February compared to 2021 and decreasing values compared to 2022. Monocytes showed decreasing values in April, June, July, October and November during 2022 compared to 2021 and decreasing values in July and August and 13.22% decreasing during spring period compared to 2021. Over the 3-year period, Neutr values are positively correlated with seasonal variations in environmental temperatures to which the horses were subjected. Furthermore, environmental temperature was inversely related to seasonal fluctuations of Lymph, RBC, HGB and HCT. Relative humidity was positively associated to the seasonal variations observed for Lymph and negatively correlated with Neutr. The non-significant variation during the different seasons and years indicated that

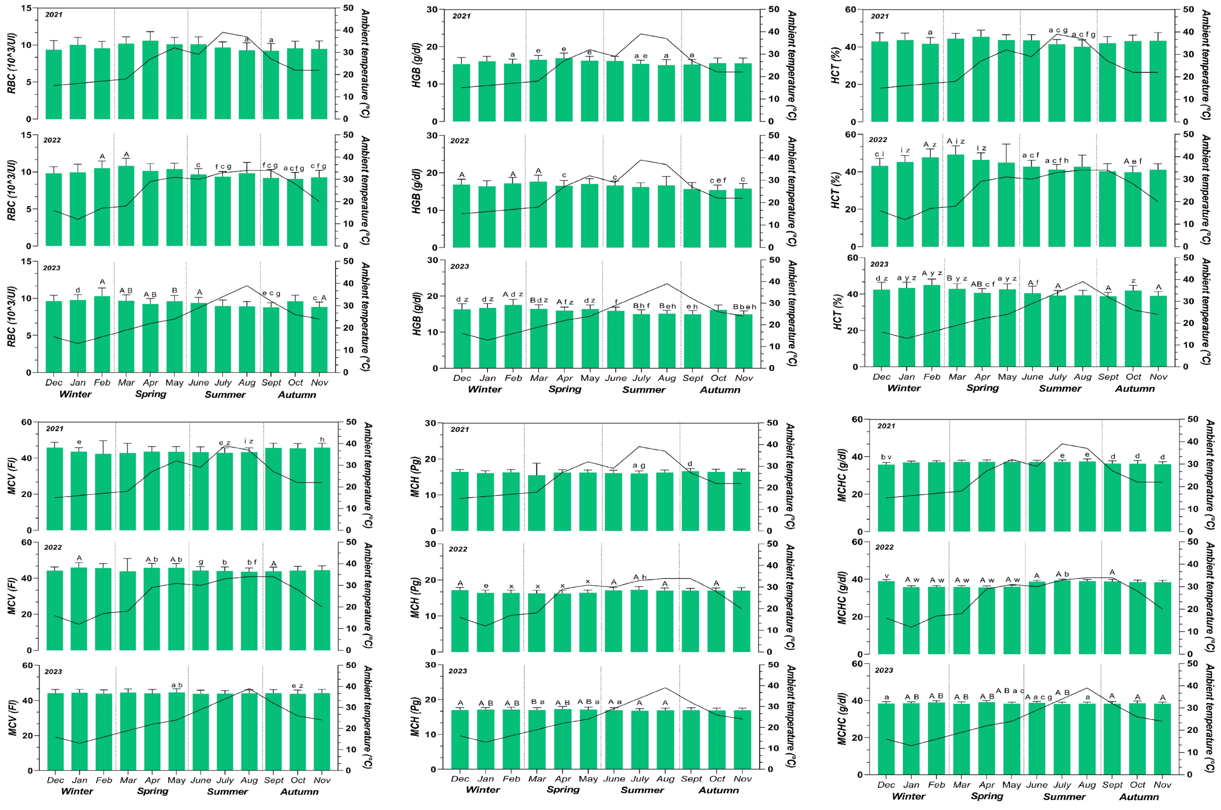

FIGURE 2
Mean values ± standard deviation (±SD) of RBC, HGB, HCT, MCV, MCH, MCHC obtained from a monthly monitoring of 25 horses during a 3-year (2021–2023) period considering the four seasons with monthly fluctuations of the max ambient temperature during the monitoring period. Significances among months ($p < 0.05$): ^{a} vs. April; ^{b} vs. June, ^{c} vs. March, ^{d} vs. August and ^{e} vs. December, ^{f} vs. February, ^{g} vs. May, ^{h} vs. January, ^{i} vs. October, ^{z} vs. September and November, ^{y} vs. July and August, ^{x} vs. June and July, ^{v} vs. January, February, March, April, May, ^{w} vs. June, July, August, September, October, and November significances among years ($p < 0.05$): ^{A} vs. 2021; ^{B} vs. 2022.

horses were adapted to different climatic conditions without being influenced. For this reason, changes in hematological values are essential in determining the adaptation of animals to the environment (31, 32). Adaptation of the physiological status of animals toward seasonality as observed by the present study depends on the degree of climate change. Therefore, it is necessary to pay attention to the degree of adaptation of the physiological parameters we analyzed even at the diagnostic level, which may lead to an imbalance of the subject's immune status, states of anemia, electrolyte or protein imbalance as observed in bulls and athletic horses, considering the exercise influence (66, 67). This information underscores the need for season-specific health management strategies in domestic animals (68, 69).

Therefore, it is necessary to provide practical management guidance for the sport horse especially in order to safeguard the state of health and athletic performance by, for example, performing exercise during specific hours of the day, ensure spacious and ventilated shelters to manage heat stress as well as implement sheltered shelters in innovative facilities to cope with a wide variety of external weather conditions considering future climatic alterations due to global warming such as floods, tornadoes, hail or fires. The present study offers a preliminary approach to the impact of climate change on physiological parameters in horses. Therefore, it would be advisable in future studies to extend the monitoring period to highlight a more significant impact of climate change on both hematological parameters indicating the subject's health status and on more specific blood parameters that could indicate tissue damage, organ damage, and more specific effects due to environmental adaptation.

5 Conclusion

Although no significant variation between monitoring years was found for environmental parameters, certain significant variations in hematological parameters were observed over the 3-year period. The climatic changes showed slight increases in environmental temperatures, fortunately not significant for the 3 years analyzed. Similarly, the hematological variations observed from 2021 to 2023, correlated with the environmental parameters, showed significant variations that were nevertheless comforting as they remained within the horse's physiological range. This preliminary study of 3-year period cannot allow to assess a proper long-term climate change effect, nor to be certain of its impact solely on the haemogram values in the horse, but this study might be helpful for providing information on the hematological profile according to seasonal changes. Therefore, an input could be given

TABLE 2 Percentage variations in hematological parameters in horses between years for each season during the study period.

Experimental conditions	Winter	Spring	Summer	Autumn
2021–2022				
WBC (10^3/Ul)	8.79	−2.49	−3.27	−7
Neutrophils (10^3/Ul)	14.96	7.91	0.64	−1.16
Lymphocytes (10^3/Ul)	3.03	−10.06	−7.37	−0.73
Monocytes (10^3/Ul)	−9.66	−19.10	−9.87	−14.19
Eosinophils (10^3/Ul)	16.88	1.13	−14.85	9.64
Basophiles (10^3/Ul)	1.01	0.69	8	18.87
RBC (10^6/Ul)	1.86	2.19	−0.24	−1.49
HGB (g/dl)	3.56	3.30	6.17	1.44
HCT (%)	4.42	5.45	1.42	−5.06
MCV (Fl)	7.66	1.27	1.92	−3.04
MCH (Pg)	1.52	17.54	6.75	3.32
MCHC (g/dl)	−3.13	−3.69	4.81	6.74
PLT (10^3/Ul)	0.32	26.75	−0.03	−2.92
2022–2023				
WBC (10^3/Ul)	1.18	−5.66	−3.33	5.74
Neutrophils (10^3/Ul)	3.89	−7.44	−0.17	10.3
Lymphocytes (10^3/Ul)	1.14	−3.69	−6.58	−0.30
Monocytes (10^3/Ul)	−2.66	13.64	8.97	14.93
Eosinophils (10^3/Ul)	0.71	60.19	21.29	26.78
Basophiles (10^3/Ul)	18.40	24.53	−1.82	−2.26
RBC (10^6/Ul)	0.74	−8.96	−5.24	−0.90
HGB (g/dl)	5.26	−4.57	−6.73	−1.56
HCT (%)	−2.93	−9.18	−5.83	−1.05
MCV (Fl)	−3.44	3.03	0.11	−0.02
MCH (Pg)	4.70	1	−1.34	−0.43
MCHC (g/dl)	8.45	7.82	−1.44	−0.27
PLT (10^3/Ul)	5.35	−2.04	−2.25	0.05
2021–2023				
WBC (10^3/Ul)	7.72	−8.73	−7.49	−2.70
Neutrophils (10^3/Ul)	14.80	−1.24	−2.22	−3.91
Lymphocytes (10^3/Ul)	2.82	−16.34	−14.42	−1.88
Monocytes (10^3/Ul)	−8.04	−13.22	−5.71	−3.77
Eosinophils (10^3/Ul)	6.46	29.52	−0.58	31.06
Basophiles (10^3/Ul)	3.11	−9.33	−2.87	2.74
RBC (10^6/Ul)	2.21	−7.38	−5.68	−2.92
HGB (g/dl)	8.47	−1.73	−1.17	−0.44
HCT (%)	0.90	−5.32	−4.75	−6.36
MCV (Fl)	1.26	2.99	1.95	−3.11
MCH (Pg)	6.26	5.92	5.24	2.85
MCHC (g/dl)	−0.29	3.82	3.28	6.44
PLT (10^3/Ul)	1.37	18.95	−5.38	−4.41

Top panel percentage increases (positive values) and decreases (negative values) between 2021 and 2022. Middle panel: percentage increases (positive values) and decreases (negative values) between 2022 and 2023. Bottom panel: percentage increases (positive values) and decreases (negative values) between 2021 and 2023.

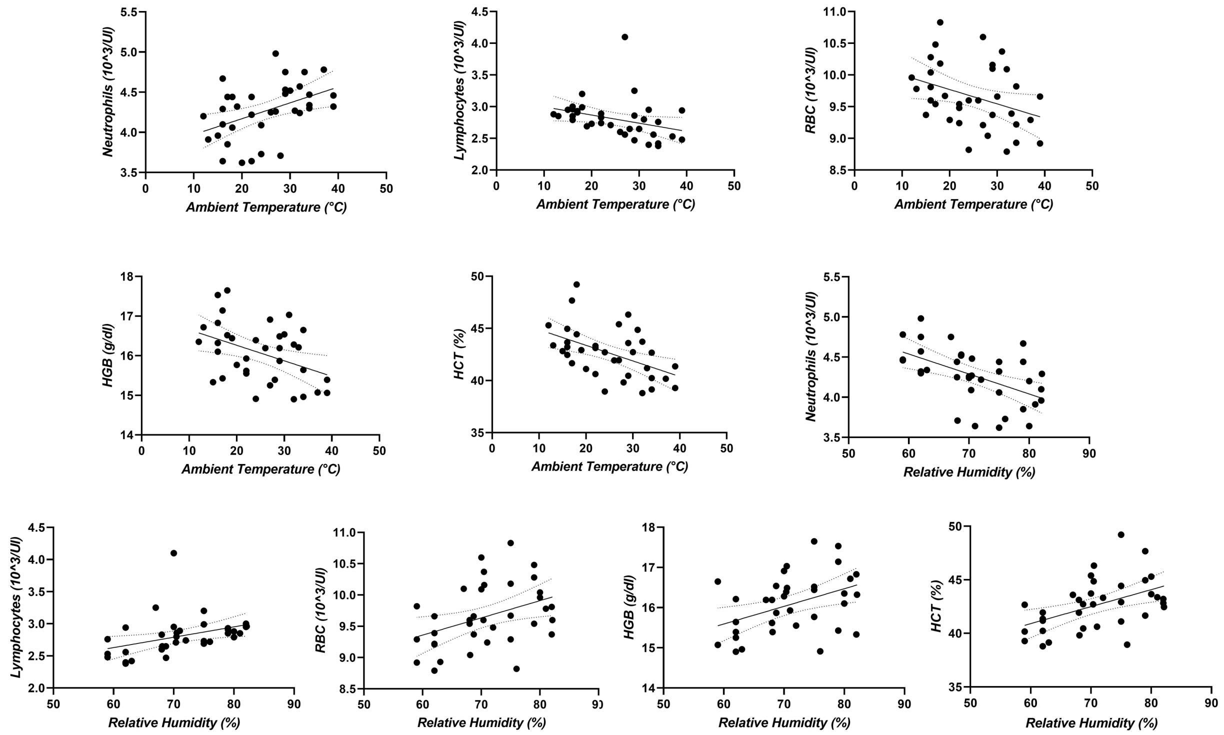

FIGURE 3
Regression lines and Pearson correlation coefficient (*r*) between the monthly values of hematological parameters and 95% confidence interval for monthly mean max ambient temperature, chosen as a representative value, and relative humidity for all years.

for future studies on the effects of climate change on the health of domestic animals as well as in humans and the productive economic impact thereof.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

The animal studies were approved by Kastamonu University Animal Experiments Local Ethics Committee. The studies were conducted in accordance with the local legislation and institutional requirements. Written informed consent was obtained from the owners for the participation of their animals in this study.

Author contributions

ÖD: Data curation, Writing – original draft. FA: Formal analysis, Methodology, Resources, Writing – original draft. BM: Writing – review & editing. KT: Writing – original draft. SB: Writing – original draft. FF: Writing – review & editing.

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Index-based livestock insurance schemes to manage climate risks in Ethiopia: determinants of farmer's willingness to pay and lessons learned from Dasenech district, South Omo

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Livestock insurance, an important risk management tool, is gaining popularity in Ethiopia. Proper investigation is needed to expand its adaptability throughout the country. This study was designed to explore the willingness and payment capacity of farmers in Southern Ethiopia to pay for index-based livestock insurance as an alternative solution to climate risk mitigation. A mixed research method was employed to gather data from primary and secondary sources. Cross-sectional data were obtained from 157 cattle farmers, drawn randomly from the study area. The study also used key informant interviews and focus group discussions to collect qualitative data. Descriptive statistics, inferential tests, and double-hurdle model were used to analyze quantitative data. Word descriptions and thematic analysis were employed for qualitative data analysis. The results of the study showed that a significant proportion of farmers were willing to pay for IBLI services. The findings also suggested that the demand for index-based livestock insurance seemed to be influenced by a number of factors. Those households that are headed by a men, who are better educated, who are better experienced in farming system, and those who have access to credit and training are more likely to pay for the insurance. Farmers' perception of weather-related risks and awareness about insurance also influenced farmers' willingness to pay positively. Furthermore, farmers with larger assets, such as land and livestock, have more confidence in paying capacity for insurance. Farmers with mass media access were more likely to pay for IBLI. However, households with larger number of household members and those who perceived the cost of the insurance premium as unaffordable are less likely to purchase the IBLI. These significant factors impacting households' willingness to pay for the insurance services must be considered in adaptation pathways. The Dasenech district case study suggests that IBLI can effectively mitigate climate risks and be applied to other regions with similar socioeconomic characteristics and production systems.

KEYWORDS

index-based livestock insurance, climate risk mitigation, willingness to pay, normalized differential vegetation index, double-hurdle model

1 Introduction

As in other Horn of African countries, Ethiopian pastoralists are exposed to a variety of natural, economic, and climate risks (Kahsay et al., 2020; Melketo et al., 2021). Pastoralists in Ethiopia continue to be vulnerable to complex challenges caused by both natural and policy factors, despite the fact that the livestock production sector is a vital source of stability and support for the nation's socioeconomic state (Jing et al., 2018), accounting for 12–16% of the national Gross Domestic Product and 30–35% of the agricultural GDP (Gebrekidan et al., 2019). The continued dependence on rain-fed dryland production systems, coupled with the lack of well-developed infrastructure and credit and insurance markets intensifies the effects of these risks (Ejeta, 2019).

It is now known that climate change-induced drought events push dry land systems to cross biophysical thresholds, causing a long-term drop in livestock productivity (Guo and Bohara, 2015) and substantial loss of livestock (Castellani and Viganò, 2017; Ejeta, 2019). Periodic droughts which aggravate the dry seasons, loss of pastures, and widespread cattle deaths have become a common feature. Ethiopian farmers experienced multiple drought patterns and significant deaths from 1973/74 to 2015/16, illustrating the severity of the issue (Desta and Coppock, 2004; Angassa and Oba, 2007; Berhanu and Fayissa, 2010; Tadesse et al., 2017).

Governance issues also increase the vulnerability of pastoralists. Instead of being inclusive, the few modern development initiatives in the region are extractive (Kahsay et al., 2020). Even though it is claimed to be a vital component of the national economy, the large-scale investments' appropriation of communal resources like land, forests, and water led to development-induced displacement, the loss of pasture and grazing land, and unhealthy ecosystem for Ethiopia's pastoralists and agro-pastoralists (Fonjong and Gyapong, 2021; Kahsay et al., 2020; Melketo et al., 2021). Additionally, the livestock industry is riskier due to poor access to information systems, sustainable markets, veterinarian and consulting services, and animal health infrastructure (Gebrekidan et al., 2019). The majority of livestock hazards are linked to illnesses and the rising death rate of cattle and small ruminants, primarily due to consecutive droughts (Jing et al., 2018). One of the recommended risk mitigation strategies in such a vulnerable environment is the index-based livestock insurance product (IBLI) (Banerjee et al., 2019; Bertram-Huemmer and Kraehnert, 2015; Bertram-Huemmer and Kraehnert, 2018).

Recently, index-based insurance is increasingly being considered as an instrument to mitigate uninsured covariate risk in rural areas lacking commercial insurance access. Over the past decade, researchers, multilateral organizations, and governments have been exploring the use of microinsurance to cover the potential losses of smallholder farmers due to weather shocks (Lu et al., 2022). This alternative form of microinsurance, insurance tailored to the needs of the poor, has been offered to stimulate rural development by allowing smallholder farmers to better adapt to climate change (Mhella, 2024). Index-based insurance offers advantages over traditional insurance by reducing transaction costs, eliminating structural problems like moral hazard and adverse selection, and allowing insurance companies and insured clients to monitor the index (Mahul and Skees, 2007).

The primary ways in which index-based insurance positively impacts different dimensions of life of the poor are highlighted in the growing body of literature (Amare et al., 2019; Jensen et al., 2024; Islam et al., 2024). Insurance provides alternative risk mitigation strategies by adjusting households' ability to handle ex-post risks, potentially influencing optimal behavior before a shock is actually experienced. Cole et al.'s (2012) systematic review reveals that index-based insurance, particularly microinsurance, positively influences investment in high-risk activities, leading to higher expected profits. Haruna (2015) shows that farmers who purchase rainfall index insurance in Ghana increase agricultural investment. Belissa (2019) uses experimental methods to show that in a game setting, insurance induces farmers in rural Ethiopia to take greater, yet profitable risks, by increasing the purchase of fertilizers. Recent impact evaluations of the original IBLI pilot in northern Kenya nonetheless find income and productivity gains, on average, for IBLI policyholders he initial IBLI pilot in northern Kenya has shown an average increase in income and productivity for policyholders, according to recent impact evaluations (Jensen et al., 2015).

In East Africa, initially, IBLI was introduced to northern Kenya in 2010 (Chantarat et al., 2013; Mude et al., 2009; Mude et al., 2010; Sina and Jacobi, 2012), and then to the Borana zone of Oromia region, Ethiopia (Castellani and Viganò, 2017). However, it is evident that the demand for the IBLI is generally low and its uptake continues to be below expectations in Africa (Giné, 2009; Jensen et al., 2015). In fact, previous studies attempted to pinpoint the major reasons for the low consumption of IBLI in other African countries. Constraints such as start-up costs of premium and low financial support of government, difficulties in transferring covariance risk to international reinsurance markets, inappropriate and/or expensive delivery mechanisms, lack of a favorable environment, and ignorance of the insurance market are among the common predicaments from the supply side (Sina and Jacobi, 2012; Mahul and Stutley, 2010; Cole et al., 2009). From the demand side, premium affordability (Carter, 2012), trust in insurance providers (Cole et al., 2009), financial illiteracy (Giné and Yang, 2009), and cognitive failure (Skees, 2008; Skees and Collier, 2008) are among the major constraints. Given the heterogeneity in socioeconomic and institutional contexts, however, extrapolating these results to Ethiopian context is difficult.

Existing studies on index-based insurance adoption in Ethiopia are based on the experience of crop insurance programs that shield farmers against yield loss brought on by climate change and associated hazards (Bogale, 2015). The assumption here is that the adoption and lessons learned from the index-based insurance products would vary between crop-based and livestock-based production systems to the degree that livelihood systems, risk mitigation techniques, and the long-term welfare outcomes linked to shocks differ in both contexts. In addition, the existing study on IBLI in Ethiopia (Amare et al., 2019) focused on the causes of failure and low uptake of the insurance. However, studies that examine farmers' willingness and ability to pay for IBLI services in Ethiopia remain non-existent.

Therefore, this study would fill the knowledge gap on the area of livestock insurance and would pinpoint key lessons that help for upscaling the microinsurance as alternative means of mitigating climate risks. Hence, the central objective of this study is to examine the determinants of farmer's willingness to pay (WTP) and purchasing power for index-based livestock insurance in livestock-based farming systems of Dasenech district, south Ethiopia.

2 The context and index-based livestock insurance adoption

2.1 The context

This study is undertaken in Dasenech district of South Omo zone of the South Ethiopia regional state located 189 km away from the border with Kenya. The landscape is an arid low-land with average annual precipitation of 250 mm and temperatures averaging 42°C (Tadesse, 2023).

Three of the four targeted kebeles by the Resilience for Innovation (R4I) project (Figure 1), Fejej, Ocholoch and Gurenamarak, are pastoral, whereas Aricol, which is located closer to the Omo River, is agro-pastoral where small-scale crop production of mainly sorghum, maize, and vegetables supplement livelihoods (Getachew and Mebrahtu, 2017). The district experiences 8 months of food and nutrition security gap per annum due to the reliance on livestock as the only reliable livelihood option for most households (Tadesse, 2023). In 2016, a severe drought led to the loss of 355,622 livestock in Dasenech (Yoseph, 2022). Inadequate rainfall and water scarcity lead to malnourished livestock, increasing disease risk and mortality. Limited resources and veterinary drugs make it difficult for local communities to address these issues, leading to migration and livestock sales.

2.2 Overview of index-based livestock insurance adoption

Traditional production systems struggle to address societal challenges such as climate risks, especially in nomadic and semi-nomadic pastoralist communities. Inclusive social innovations are, therefore, required to build resilience and ensure sustainable development (Kalkanci et al., 2019). The EU has committed resources to initiate EU-Resilient Ethiopia (RESET Plus Innovation funded) projects, including the innovation for resilience (I4R) project at Dasenech district. This project introduced IBLI as a novel climate risk mitigation strategy. IBLI Dasenech's index is determined at the district level by calculating the cumulative deviation of Normalized Differential Vegetation Index (NDVI) measures, a crucial indicator for drought monitoring in Africa. The IBLI scheme, underwritten by Oromia Insurance and Sinqe bank, utilizes satellite imagery to calculate the NDVI to assess forage/vegetation scarcity. If the NDVI falls below a trigger point, payouts are made to protect core herds, based on nutritional requirements.

The I4R project trained village insurance promoters (VIPs) to serve as community advocates for IBLI and facilitate awareness creation campaigns. The project also subsidized 50–75% of insurance premiums to boost participation and included IBLI premium payments in the safety-net package, enhancing drought-affected communities' resilience and expanding insurance products. Not all the

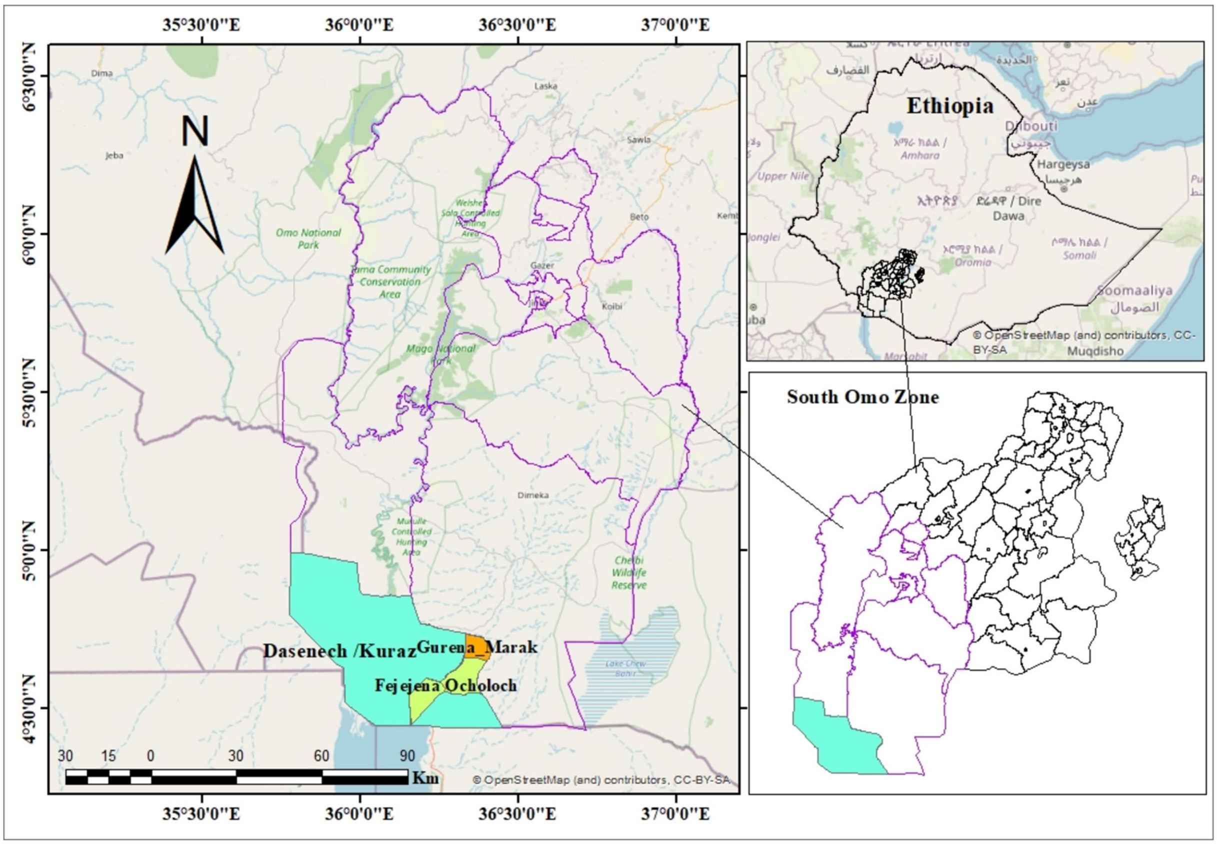

FIGURE 1
Map of the study area.

farmers at the district use IBLI, and for those who do, they do not buy for all their livestock. There are factors that underlie the decision to pay, which are what this study seeks to explore.

3 Materials and methods

3.1 Research approach

This article is part of a bigger research which involving a comprehensive household-level surveys using a mix of qualitative and quantitative methods to assess the socioeconomic and resilience capacity changes and impacts brought about by social innovations. Out of the 13 innovative projects funded by the EU-RESET Plus, this action research covered innovative project situated at the South Omo cluster. Based on Roger's (Rogers et al., 2014) innovation diffusion theory, attempts were made to analyze the extent to which communities recognize and embrace innovation. In short, it describes the extent to which beneficiaries adopt innovative technologies for societal change.

3.2 Sampling frame

The study utilized random sampling technique to select participants from four target *kebeles* (the smallest admirative units) in the district, determining a total sample size using a published table (Israel, 2013) with ±7 level of precision. This yields a sample size of 143 households out of the total population involving a list of both beneficiaries and non-beneficiaries of the innovative project being implemented in the target district. Thus, with a non-response rate of 10% and the final sample size for the study was 157 households. Then, probability proportional to size (PPS) sampling was employed to get the sample size in each kebele.

Sixty-nine percent of the sample households were men-headed and 31% women-headed. In terms of respondents, however, 59% were men and 41% men. The high proportion of women respondents was due to widowed households and husbands away for casual employment or mobility. In households (10%) where the husbands were away from the house for a long time, their wives were making decisions on important household issues relating to livestock production and IBLI payout issues. All the respondents were livestock herders and only a few (15%) were agro-pastoralists practicing dryland crop farming. Before the introduction of IBLI schemes as alternative climate risk mitigation innovations, traditional adaptation strategies such as destocking and restocking of livestock after severe catastrophes like droughts, food and cash aid, and engagement on productive safety-net programs were among the efforts taken by the respondent households in the study area.

3.3 Data collection methods

Both primary and secondary data were gathered and used for this study. Cognizant of the research goal, and the nature of the information needed on various aspects of this study, employing a single type of data and data acquisition technique is insufficient to satisfy the data requirements. This research, therefore, employed mixed methods to collect data from primary and secondary sources as described below:

3.3.1 Desk review

Here, attempts were made to access and critically review the field practices in line with the theory of change of the implemented pilot project, government policies, and strategic guidelines; strategic documents of the EU-RESET innovation-funded project; the project design and implementation guidelines, and project performance reports. The desk review helped examining the livestock farmers' payment trends for IBLI services and identify good practices, challenges, and lessons learned from the pilot project in Dasench district.

3.3.2 Household survey

A semi-structured interview schedule with different modules related to demographic, socioeconomic, institutional, and psychosocial factors was prepared and agreed upon with the funding agency, the Cordaid Ethiopia, and implementing NGOs before departing for fieldwork. Twenty randomly selected respondents (50% men and 50% women) comprised of five households per kebele who were not participants in the sample households for the major survey at the district were given the interview schedule in order to pre-test it before the actual survey was performed. On the basis of the results obtained from the pre-test survey, necessary modifications were made in the interview schedule. Training on Kobo Tool data gathering methods and the contents of the interview schedule were given to selected enumerators. Finally, the questionnaires were administered to 157 sampled households in the study area in the period September 10–17, 2023.

3.3.3 Focus group discussions (FGDs)

Four FGDs (one FGD per a kebele comprising six to seven participants) were conducted to gather qualitative data on farmers' adoption of IBLI, its limitations, good practices, and local knowledge on climate change and livestock production systems.

3.3.4 Key informant interview

In-depth interviews were conducted with 17 key informants. These key informants included district-level rural and pastoral development experts, development agents, Kebele administrators, and clan leaders. These people included community elders and religious leaders who were well-versed in the climate conditions, mitigation and adaptation plans, and livestock production methods of the district. The respondents were mainly heads of households (usually men) in the kebele. However, when the household head was not present at the time of the visit, the spouse was interviewed. Given that men were mobile with their herds and less available at home during the study period, the majority of the interviewees were women. Local guides assisted the interviewers in identifying the selected households.

3.4 Methods of data processing and analysis

3.4.1 Analytical technique

A review of literature on willingness to pay for agricultural insurance indicates that there are three ways of estimating farmer's willingness to pay for insurance. One is contingent valuation method, which is highly recommended in the instances where there is no or little market information (Taneja et al., 2014). However, the contingent valuation method was not used in this study because there have been different advocacy platforms that have been established and utilized for promoting the adoption of the IBLI technology and its importance for livestock headers particularly by the implementing NGOs in the context of Dasenech district.

Various studies have used either the double-hurdle model or the Heckman's sample selection model in determining the willingness to pay for insurance (Gabre-Madhin et al., 2003; Wodjao, 2008; Yu and Abler, 2010). In this study, the double-hurdle model was adopted based on its advantage over the Heckman's selection model. The Heckman sample selection model assumes that no zero response will be present in the second hurdle of the analysis once the first hurdle is passed while the double-hurdle, on the other hand, recognizes the possibility of zero observations in the second stage (Wodjao, 2008). The possibility of zero response is as a result of the fact that the livestock farmer may refuse to answer due to a lack of knowledge or how complex the questions are perceived to be. In addition, some pastoralist household heads may only have partial information concerning their willingness to pay (Yu and Abler, 2010). For such a case, it is possible that respondents cannot give a number representing their WTP but may recognize the fact that they have a positive WTP.

Smith (2002) and Smith and Watts (2019) suggested a double-hurdle model in which adoption behavior consists of two decisions: an adoption decision, which is a binary choice, modelled using a Logit; and a WTP amount decision, which is a truncated regression model. The double-hurdle is used in a situation where an event may occur or not and when it does, it takes on continuous positive values (Gabre-Madhin et al., 2003). It is assumed that the livestock farmer is faced with hurdles in the decision-making process. Hence, the decision to pay is made first followed by the decision on how much to pay for the insurance. The two equations are assumed to be independent.

This study focuses on utility maximization, a theory that suggests farmers make decisions based on maximizing utility rather than just profit from the index-based insurance (McConnell et al. 2009). The utility of a pastoral household is given as U_{ij}, from choosing alternative j. A pastoralist household will choose whether or not to adopt livestock insurance depending on the relative utility levels associated with the two choices. Therefore, the probability that alternative j will be chosen is given by

$$P(yi-j)=p(Uij\geq Utk\diagdown X,\varnothing k=j)=P\begin{pmatrix}\varepsilon tk-\varepsilon ij\leq X'ij\beta j-\\ X'ij\beta k\diagdown X,\phi k\neq j\end{pmatrix}$$

where yi is the observed outcome for the ith observation. $i=1,\ldots,N$ indexed the livestock farmer, $j=1,\ldots,j$ and $k=1,\ldots,k$ are the alternatives being considered, X is a vector of livestock farmer, farm and institutional characteristics, β is a vector of parameters to be estimated, and ε is the stochastic random error. Even though the difference in utilities (Vi) of adoption and non-adoption are unobserved,

$$Vi=Uij-Uik$$

The decision of a farmer is taken as a binary outcome such that

$$Ji\in j=\{1\text{ if }V>0,\ 0\text{ otherwise }\}$$

The assumption here is that livestock herders choose index-based livestock insurance adoption or non-adoption based on their highest utility level, deciding on the option that enhances their highest level of utility.

Accordingly, the first equation in the double-hurdle relates to the willingness to adopt livestock insurance scheme. A probit regression on the willingness to adopt or not is modeled as:

$$WTI=1\ if\ WTI>0 \qquad and\ WTI\leq 0$$

$$WTI=zi'\alpha+\varepsilon_i$$

WTI is a dichotomous variable, which assumes a value of 1 and 0 otherwise, z is a vector of a livestock farmer, farm and institutional characteristics, α is a vector of parameters, and $\varepsilon\varepsilon_i$ is the error term.

The empirical model for livestock farmer's willingness to adopt index-based livestock insurance is specified for this study as.

$$WTI=\beta_0+\beta_1 Age+\beta_2 Gender+\ldots\beta_i Z+\ \varepsilon_{i.}$$

WTI is the probability that an ith livestock farmer is willing to adopt the livestock insurance. β_i are the coefficients of the explanatory variables. ε_i is the error term.

The second hurdle which estimates the amount (premium) livestock farmers are willing to pay is estimated using a regression truncated at zero. It is expressed as

$WTPamt_i$ = WTPamt_i*, if WTPamt_i* > 0 and if WTPamt_i* = 0 otherwise WTPamt_i* = x'iβ+ui

where WTPamt_{i^*} is the observed response on how much livestock farmers are willing to pay for livestock insurance. χ is the vector of farmer, farm and institutional characteristics, β is a vector of parameters, and $u_i$is the error term which is randomly distributed.

The empirical model of the truncated regression model (tobit model) is specified for this study as

$$WTPamt_i=\beta_0+\beta_1 Age+\beta_2 Gender+\ldots+\beta_i Z+\varepsilon_i$$

where $WTPamt_i$ is the amount an ith livestock farmer is willing to pay, β_i are parameters to be estimated, and ε_i is the error term.

3.5 Definition of variables and hypothesis

The potential explanatory variables expected to influence the decision to adopt IBLI and their expected sign of influence are summarized in Table 1.

4 Results and discussion

4.1 Results of the descriptive statistics

4.1.1 Demographic and socioeconomic characteristics of the respondents

A deliberate effort was made to consider gender in the sampling process when choosing respondents in the survey. This was based on

TABLE 1 Definition and expected signs of explanatory variables.

Variables	Definition	Expected signs
Age	Age of household head (year)	+
Sex	Sex of household head, 1 if a man and 0 otherwise.	+
Family size	Family size of a household in Adult Equivalent (AE)	+
Education	Education of household head in years of schooling	
Experience	Respondent's loss experience of livestock (dummy)	+
Land size	Total land holding in hectares	+
Livestock	Total livestock holding in Tropical Livestock Unit	
Off-farm	Dummy for participation in off-farm activities: 1 = Yes, 0 = No	+
Credit	Whether a household head receives credit, 1 = yes,0 = no	+
Insurance history	Whether a household had a previous history of insurance, 1 = yes,0 = no	+
Cost of premium	Household perception about the affordability of the cost of IBLI premium, 1 = yes,0 = no	–
Trust	Household perception about trust built on IBLI schemes, 1 = yes,0 = no	+
Training	Whether the respondents have received training on IBLI, 1 = yes, 0 = no	+
Membership	Number of social groups households have been members	+
Weather risk perception	Dummy for weather risk perception: 1 = yes, 0 otherwise.	+
Climate information	Dummy for receiving climate warning information: 1 = yes, 0 otherwise	+
Institutional support	Institutional support obtained from government organizations (GOs) and non-government organizations (NGOs), 1 = yes,0 = no	+
Insurance awareness	Dummy for having awareness about insurance, 1 = yes,0 = no	
Extension	Frequency of extension agents' contact	+
Livestock market	Availability of diverse livestock market outlets 1 = yes,0 = no	+
Livestock illness history	Whether the household experience livestock diseases during the past 1 year, 1 = yes,0 = no	+
Accessibility	Accessibility of a household to the insurance agents in their locality, 1 = yes,0 = no	+
Media	Frequency (per week) to attend radio for insurance information	+

the rationale that women and men might interact differently with pastoral and agro-pastoral life systems and the associated difference in the decisions to pay for IBLI packages. Concerning the gender distribution, women represent 37.58% of the total respondents to the survey questions, and the positive responses to adopt IBLI package overweigh by both sex categories, as illustrated on Table 2. The calculated p-value indicated a statistically significant association between gender and farmer willingness to pay for insurance at a 0.05 significance level. The study reveals that the willingness to pay for IBLI services significantly differs based on the gender differences among farm household heads.

Four age categories were used to analyze the age data. More than half of the respondents (52.23%) fall under the age range of 25–35 years, 20.38% were below 25 years, 16.56% were adults under the age category 36–45 years, and the rest 10.83% of the respondents comprise older people groups whose age is more than 45 years. It was found that the vast majority of pastoralist and agro-pastorlist households in Dasenech (85.35%) were illiterate, who cannot read and write. It indicates that access to education is among the pressing challenges that Dasenech communities are facing. Over half of the sample households (63.66%) had large families with six or more members, indicating high food and sustenance demands. The p-value strongly suggests that the existence of significant association between the age difference and farmer's willingness to pay for the index-based insurance.

The average land holding size of agro-pastoral communities of Dasenech is 1.29 ha per household (Table 3) whereas the average farm land size of the households who purchased the index-based insurance is 1.32 ha per household, which overweighs the land size of those who did not purchase the insurance (1.20 ha). This implies that land size has a positive association with the household's decision and/or willingness to pay for the insurance. The average herd size per household is 2.20 in Topical Livestock Unit. It is worth mentioning that households with an average larger livestock size showed better willingness to pay for the insurance than those who had averagely lower herd size.

The study revealed that households who are not diversifying their livelihoods from livestock dependence to off-farm income-generating activities (44.59%) outperformed those participating in off-farm activities (28.03%) in purchasing insurance (Table 4). The implication is that participation on off-farm activities had a negative association with willingness to purchase the insurance. The calculated p-value, however, showed that the difference in farmer's willingness to pay for the insurance between off-farm participant and non-participant households is insignificant. On the contrary, the analysis revealed that household saving culture positively influences the farmer's willingness to pay for the insurance, as indicated in Table 4. The willingness to pay for insurance varies significantly between those who practice saving and those who do not.

TABLE 2 Demographic characteristics of households with their willingness to pay for IBLI package.

Variables	Categories	Did you purchase an Index-Based Livestock Insurance package?		Total (N = 157)	X^2 value
		Yes (N_1 = 114)	No (N_2 = 43)		
Sex	Men	64 (40.76)	34(21.66)	98 (62.42)	6.99***
	Women	50 (31.85)	9 (5.73)	59 (37.58)	
Age	<25 years	19 (12.10)	13 (8.28)	32 (20.38)	22.52***
	25–35 years	52 (33.12)	30 (19.11)	82 (52.23)	
	36–45 years	26 (16.56)	0.	16 (16.56)	
	> 45 years	17 (10.83)	0	17 (10.83)	
Education	Cannot read and write	95 (60.51)	39 (24.84)	134 (85.35)	2.58
	Grade 1–4	13 (8.28)	4 (2.55)	17 (10.83)	
	Grade 5–8	4 (2.55)	0	4 (2.55)	
	Grade 9–12	2 (1.27)	0	2 (1.27)	
Household size	1–3	8 (5.10)	0	8 (5.10)	9.71***
	4–6	29 (18.47)	21 (13.38)	50 (31.85)	
	>6	77 (49.04)	22 (14.01)	99 (63.06)	

***, and ** Indicate the level of significance at 1 and 5%, respectively.

TABLE 3 Socioeconomic characteristics of respondents with their willingness for the insurance.

Continuous variables	Categories	Did you purchase any Index-Based Livestock Insurance package?		Total (N = 157)	t-value
		Yes (N_1 = 114)	No (N_2 = 43)		
Land size	Mean (SD)	1.32 (0.07)	1.20 (0.11)	1.29 (0.06)	0.42
Livestock	Mean (SD)	2.33 (0.14)	1.85 (0.17)	2.20 (0.13)	0.05

TABLE 4 Socioeconomic characteristics of respondents with their willingness to pay for the insurance.

Dummy variables	Category	Did you purchase any Index-Based Livestock Insurance package?		Total (N = 157)	X^2 value
		Yes (N_1 = 114)	No (N_2 = 43)		
Off-farm	Yes	44 (28.03)	15 (9.55)	114 (72.61)	0.18
	No	70 (44.59)	28 (17.83)	43 (27.39)	
Saving	Yes	52 (33.12)	62 (39.49)	114 (72.61)	11.45***
	No	7 (4.46)	36 (22.93)	36 (22.93)	

*** and ** Indicate the level of significance at 1 and 5%, respectively.

4.2 Payout trends for index-based livestock insurance at Dasenech

In this section, an attempt was made to examine farmer's experience in purchasing IBLI at Dasench district of South Omo zone, Ethiopia. To understand this, data on the sales of IBLI during the I4R project pilot period were obtained from CST Ethiopia (CAF + D + SCIAF Trocaire) interim and endline reports and were reviewed. BLI insurance contracts were sold during two sales periods—January to February and August to September—before the start of both short and long rainy seasons. Index readings for each sales period were announced, and indemnity payments were made to policyholders if a strike rate is triggered at the end of the season.

Within the four project kebeles, a total of 1,414 households purchased IBLI insurance (Figure 2) during the first and second sales windows (January–February and August–September 2022). Out of these, 255 (45 M, 210F) households were subsidized 50% of the premium by the project to cover the insurance premium. The community faced hardships due to drought and fluctuating food costs in the district during the second sales window. The field office, therefore, decided to increase the size of subsidy to 70% as well as the number of households to get the subsidy to 439.

The general trends observed during the period of 2022–2023 in Figure 3 is an increase in the number of households that participated in IBLI and the number of livestock insured under the insurance product. Between the two piloting years, the number of households participating in the IBLI and the number of livestock insured

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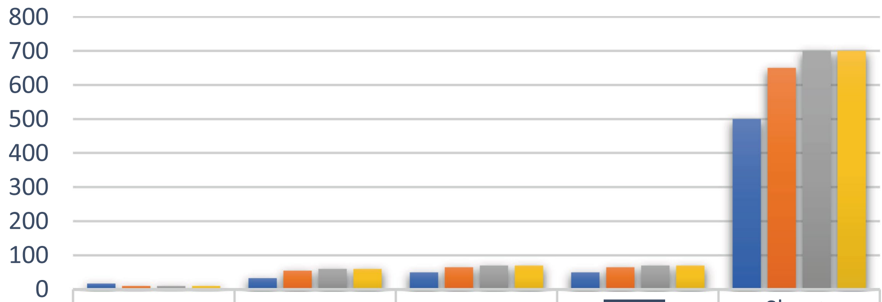

	Male	Female	Total	Livestock insured	
				[redacted]	Shoat
Arikol	17	33	50	50	500
Fejeje	10	55	65	65	650
Gurenarama	10	60	70	70	700
Ocholoch	10	60	70	70	700

Arikol Fejeje Gurenarama Ocholoch

FIGURE 2
Households purchased insurance during the two sales windows (2022).

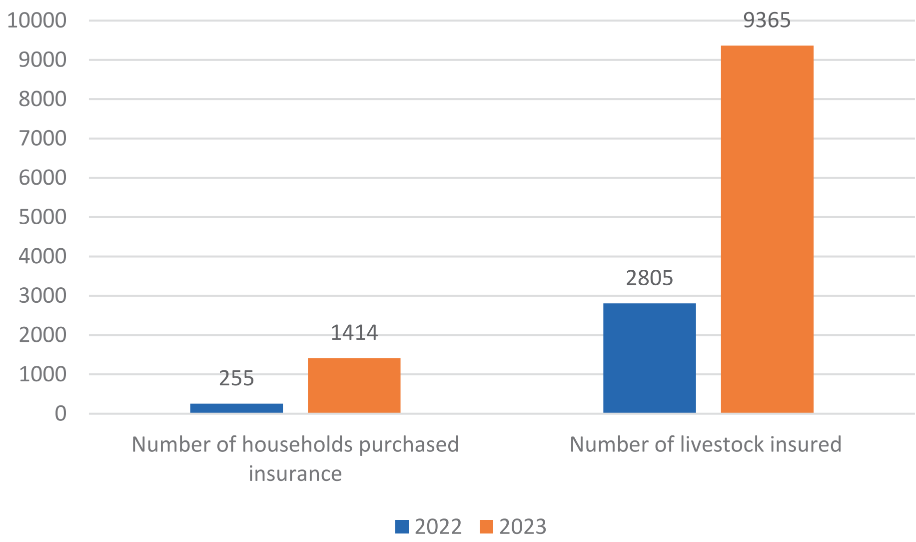

FIGURE 3
Trends in the willingness to pay for IBLI over years in Dasenech.

increased from 255 to 1,414 and 2,805 to 9,365, respectively. This shows that over time the pastoralists/agro-pastoralists had become more acquainted with the importance of the IBLI and hence demanded more insurance service. The information acquired from the key informant interviews also confirmed the increasing demand for IBLI in their locality.

This can be explained by the extensive awareness-raising done on IBLI at *kebele* level by village insurance promoters throughout the project period. This is also probably due to the fact that the drought occurred in 2022 and 2023 in the area influenced farmers to participate in the insurance and increase the number of their livestock to be covered under the insurance scheme. The result also indicates the relevance of the insurance scheme for pastoralist/agro-pastoralists as it protects their main livelihood asset from drought which has been recurring in the district.

4.3 Factors affecting agro-pastoralists' WTP for the index-based livestock insurance

Agro-pastoralists' WTP for the IBLI was influenced by various individual, farm level, and institutional factors. The double-hurdle model structure is advantageous as it can handle multicollinearity or overestimation in variables, as it could identify and remove variables with similar problems during estimation. Out of the variables put into the double-hurdle model, livestock illness history and the constant were dropped from the first stage model due to multicollinearity problem. The results were set and discussed under categories of individual, institutional, and farm-related factors for convenience and to facilitate understanding.

The results indicated that (Table 5) WTP for the insurance was found to be better among men-headed households than their counterparts. This association was positive and significant at a 5% probability level. This is an indication that farm households headed by men are more likely to adopt and pay for the IBLI. Being a man-headed household would increase the likelihood of household's willingness to pay for the insurance by 4.1%. This is probably because traditionally men in such a patriarchal community are favored to have better access to information about the IBLI as an alternative solution and have better decision-making power at the household level than their counterparts do. This finding is in line with Castellani and Viganò (2017) who stated that farmers with men-headed households showed better willingness to pay for productive technologies including index-based insurance to manage risks associated with crops and livestock failure.

The results also indicated that pastorlists/agro-pastoralists who were better educated were better willing to pay for the insurance than those who were less educated do. Farmers' education status positively and significantly affected their WTP for the index-based insurance at a 1% probability level. A change in 1 year of educational status would bring a change in farm household's WTP by 1.4%, considering other things are constant. Agro-pastoralists who are better educated would have better awareness and decision-making power to adopt alternative solutions like IBLI to mitigate livestock losses and related climate risks.

The implication for this finding is that households with better access to education are more likely to pay for indexed-based livestock insurance, which has a potential to reduce the adverse effect of extreme droughts on livestock production and productivity, particularly in the moisture-stressed areas like Dasenech. First, education helps farmers find and use information related to livestock production. Therefore, education can facilitate the dissemination and enhanced use of new technology through informed decision-making. Second, education helps farmers anticipate the effects of climate change and understand the potential benefits of IBLI to minimize the adverse impacts of climate change. IBLI products can be challenging for low-literate farmers, but education can help reduce their vulnerability to climate change and variability. It also reduces cognitive failure, which could happen probably due to malnutrition and stunting in the poor households, which in turn affects their willingness to invest in the poorly tailored, risk-related microinsurance (Skees et al., 2008). This result supports the view of numerous studies that show the positive impact of education on farmer's decision to adopt crop and livestock insurance. While studying the willingness to pay for crop insurance, Abebe and Bogale (2014) from Ethiopia reported that farmers with more literacy rates were more interested in rainfall-based insurance and willing to pay higher amount. More educated farmers are likely to appreciate crop insurance issues better than their less educated counterparts.

Household size is the other demographic characteristics found to positively and significantly influence WTP of the households at a 5% probability level (Table 5). A unit increase in family size by Adult Equivalent would result in 3.1% increase in family's WTP for the IBLI, provided that other things remain constant. Empirical studies have reported diverse relationships between family size and WTP for

TABLE 5 First-stage results on maximum likelihood estimates of willingness to pay for livestock insurance.

Variable	Coeff.	(dy/dx)	Std.Err.	*Z*
Sex (*men**)	0.041	0.041	0.011	3.46**
Age (*<25 years**)	−0.035	−0.035	0.018	−1.91
Education (*Cannot Read Write**)	0.014	0.014	0.007	1.88***
Household size (*<4**)	0.031	0.031	0.012	2.43**
Livestock (TLU)	0.009	0.009	0.003	2.43**
Land size (ha)	0.022	0.022	0.007	3.15***
Experience (years)	0.005	0.005	0.002	2.39**
Credit (*Yes**)	−0.022	−0.022	0.032	−0.69
Saving (*Yes**)	−0.605	−0.605	0.452	−1.34
Weather risk (*Yes**)	0.052	0.052	0.012	4.22***
Livestock market (*Yes**)	−0.025	−0.025	0.015	−1.69
Media use (*Yes**)	0.559	0.559	0.082	6.75***
Training (*Yes**)	0.147	0.147	0.035	4.14***
Insurance awareness (*Yes**)	0.083	0.083	0.027	3.07***
Cost of premium (*Yes**)	0.083	0.083	0.027	1.60
Trust (*Yes**)	−0.052	−0.052	0.026	1.98
Accessibility (*Yes**)	0.484	0.484	0.046	10.36***
Extension frequency (1*)	−0.0037	−0.0037	0.0053	−0.71

*** and ** Indicate the level of significance at 1, and 5%, respectively. * Indicates base category.

microinsurance. According to Atino (2020), Castellani and Viganò (2017), for instance, negative relationship was reported between family size and WTP of households for crop insurance in Kenya. In contrast, big family size was reported as positively influencing household's WTP for livestock insurance in the same country — Kenya (Ouya et al., 2023), and Burkina Faso (Fonta et al., 2018). Similarities in the insurance types and context of pastoralist production systems may therefore account for the congruence between the results of the current study in Ethiopia and those of the later empirical studies in Kenya and Burkina Faso.

The econometrics result further showed that agro-pastoralists' previous insurance history positively and significantly influenced the farmer's WTP for the insurance. For one-year previous experience of household on insurance, the odds ratio in favor of households' WTP for IBLI will increase by the factor of 0.005 (Table 5). This might be due to the fact that a household that has previous history of insurance would have some basic information about the program's benefits and would develop better tendency to accept and pay for IBLI than the one who lacks the experience and prior knowledge about insurance. This result suggests a strong and continuous need for awareness creation and training on this insurance product. The result supports the findings of earlier studies on the effect of insurance history of a household on the uptake and willingness to pay for health insurance (Mude et al., 2010).

Farmers' loss experience of livestock was also identified as a significant variable influencing their WTP for IBLI among pastoralist/agro-pastoralist communities. A unit increase in livestock loss experience of a farm household would result in a 0.5% change in the farmers' WTP for the IBLI services. A handful of empirical literature (Aheeyar et al., 2023) agrees with this findings. The more a farmer experiences loss of livestock due to drought and related calamities, the more he or she could sense about risks of livestock and/or crop loss in the drought-prone environments like Dasenech. This experiential knowledge would boost the farmer's decision to look for innovative solutions like IBLI and influences the decision on making investments like purchasing insurance as a gateway out of the risk.

It is recognized that two types of land rights — communal and private land rights — being exercised in the pastoral and agro-pastoral areas of the country. This study only considered the land that individual pastoralist/agro-pastoralist household posesses. Land ownership is a critical factor for both crop and livestock production systems, and adoption of agricultural innovations for the farming community is highly influenced by the landholding size of the farmer. The results of this study indicated that the size of cultivated land is positively and significantly related to the farmer's WTP for IBLI in response to climate variability and change in the study area. The econometric results further revealed that the odds ratio in favor of purchasing IBLI increases by factor of 2.2 ($P \leq 0.01$) (Table 5). This is probably due to the fact that large land size would empower the farmers as it gives them enough pasture for grazing their herds and practicing crop production. Similarly, a positive correlation was reported between the farmer's WTP for agricultural insurances and farm size (Osipenko et al., 2015). This is probably because farmers with larger farm sizes tend to have more advantage for the adoption of innovations due to economies of scale.

Livestock holding in TLU positively influences the household's decision to purchase IBLI at a 1% significance level (Table 5). First, this might be attributed to the fact that farmers having larger herd size relatively feeling highly vulnerable to risks emanating from climate change and variability; second, having large number of livestock enhances herders' financial capacity and so that they can make a decision to purchase insurance for their livestock. Under a situation where there is a decline in natural pastures due to climate change and variability, many pastoralists opt to store forage and save water using the indexed livestock insurance. This result is inconsistent with prior expectation and inconsistent with previous studies (Chantarat et al., 2013; Arshad et al., 2016).

The results presented that a farmer's WTP for IBLI increases by factor of 5.2 ($P \leq 0.01$) with a unit increase in farmer's perception of risks related to climate change (Table 5). This implies household heads who perceived that the weather-related risk will often exert pressure on their livelihoods and drought experienced in the near past were more likely to pay for index insurance as a protective measure. Pastoralists/agro-pastoralists who perceived the changing climate favors the use of IBLI as a risk transfer measure and as an important means for mitigating climate change-related livestock death. The result is in conformity with the earlier studies (Aidoo et al., 2014; Bogale, 2015).

The qualitative result further supports the notion that households who perceived the changing climate tend to adopt the IBLI. During a case story narration, a 58-year-old agro-pastoralist with rich experience at Fejej kebele explained that:

> *"Climate is changing over years. Like 20/30 years ago in my age, drought was not frequent. Drought occurs every 5 or 6 years. Nowadays, however, drought is very frequent. Rain is not coming in the expected seasons. It is very erratic; it comes late, but goes early. Heat-induced livestock diseases are occurring frequently. Reduced livestock productivity and even complete loss due to death caused by frequent and long drought are highly affecting my family livelihood. This pushed me to look for relatively sustainable adaptation mechanism. I found and understood the very importance of IBLI that is promoted in our district. I personally purchased this insurance since the introduction of the project."*

The study also revealed that a unit increase in awareness about livestock insurance would increase the farmer's WTP for insurance by factor of 8.3. In the study, the respondents were considered aware if they had received information on agricultural insurance through different sources like insurance companies/agents, visiting the extension officials, media, groups/cooperatives, and neighbors/relatives. These sources, particularly government offices and insurance companies/agents, have played an important role in livestock insurance adoption by creating awareness among the farmers. Insurance companies/agents have participated actively in the program because the insurance procedure for livestock insurance is scientific and possesses less chance of moral hazards, for instance, tagging of insured animals ensures insurance companies identify the right insured animals. Moral hazards arise from asymmetric information that changes the insured farmer behavior after taking insurance policy in such a way that the probability of receiving indemnity payment increases. Awareness helped agro-pastoralists to realize the need for insurance and understand the procedures of livestock insurance. The results of this study agree with the previous research findings, which pinpointed that awareness greatly influences the community's willingness to pay for health insurance as a risk management strategy (Esan et al., 2020).

As expected, access to media (defined in average frequency that a household head attends news and information on radio per a week) affected the WTP for index-based insurance positively and significantly at 1% probability. The insurer also undertakes to provide weather information through radio in the insured local language. The results indicated that listening to a radio to access information at least once a week were found to have a greater likelihood to pay for the index-based livestock insurance ($P \leq 0.01$). This might be due to the fact that the household with media access can utilize it to easily communicate and have basic information about the benefits of IBLI, so that they are better off in terms of their tendency to accept and pay for IBLI than one who do not have access to and the utilization of mass media. This result supports the findings of earlier research in Kenya, which reported the positive effect of media access on farmer's willingness to pay for microinsurance (Mude et al., 2010).

As hypothesized earlier, it was found that training access for the farmers would positively and significantly affect the farmer's WTP for insurance. The result indicated that the odds ratio in favor of WTP for livestock insurance will increase by factor of 14.3 with a unit increase in access to training, holding other variables constant. The review of the project interim report also indicated that successive training had been arranged by the project implementors on different topics including IBLI strategies, types of insurance, scope of IBLI parameters, and the claiming aspects. These training programs help the pastorlists/agro-pastoralists to realize the need for insurance and understand the procedures of livestock insurance. Thus, farmer's access to training greatly influences WTP for the livestock insurance as a risk mitigating strategy.

The econometric results (Table 5) revealed that a unit increase in accessibility of a household to insurance agents will result in an increase of the farmer's WTP for IBLI by 48.4% ($P \leq 0.01$). The probable reason is that access to insurance agents helped farmers in better understanding the insurance procedure and its benefits, ultimately motivating them to purchase livestock insurance. Livestock farmers in remote areas lack access to microinsurance and climate information, undermining the benefits of purchasing IBLI to reduce climate variability and change-induced livestock production risk. Improved road infrastructure and climate information for mobile pastoralists and agro-pastoralists can increase their WTP for insurance products, as indicated in previous empirical literature (Bogale, 2015; Arshad et al., 2016). The adoption of agricultural insurance in Nepal is significantly hindered by the lack of access to insurance service providers (Ghimire et al., 2024). Low insurance service procurement and WTP can be attributed to insurance agents' inability to access and effectively communicate policies to farmers (Jokhio et al., 2016).

4.4 Determinants of household's payment amount for a given livestock insurance value

Table 6 presents those factors influenced the pastoralist/agro-pastoralists' payment capacity (household's WTP amount of a given offered price or bid value) for the index-based livestock insurance. Out of the variables put into the double-hurdle model, media use and training access were dropped from the second stage model results due to multicollinearity problem.

Unlike the first-stage double-hurdle model likelihood estimates, the results of the second-stage model estimates (Table 6) show that large family size has a negative and significant effect on household's WTP amount of a given offered price or bid value for IBLI. A household's WTP bigger amounts of a given bid value of IBLI service was found to be negatively associated with large family size of the farm households ($P \leq 0.01$) (Table 6). A unit increase in family size in Adult Equivalent would result in a decrease in household's paying capacity of the bid value by 3.186 birr, holding other variables are constant. This may be linked to the household decision-making process in the context of big family size and relatively high living costs prioritizing the food and other consumption needs of the family (i.e., budgetary constraints). This finding is similar to the results of the previous studies reported in different countries such as Ethiopia (Ayenew et al., 2019); Nigeria (Oyawole et al., 2016; Esan et al., 2020); Nepal (Maskey and Singh, 2017) and Ghana (Awunyo-Vitor et al., 2013).

From the double-hurdle maximum likelihood second estimates (Table 6) of amount paid for the insurance, we could infer that the household's paying capacity is positively and significantly influenced by the herd size in TLU. The regression coefficient of herd size was also significant (below 5%) and positively affects household's paying

TABLE 6 Maximum likelihood estimates of amount paid for the livestock insurance.

Variable	Coeff.	Std. Err.	Z
Sex (*men**)	0.972	0.605	1.60
Age (*<25 years**)	−1.735	0.949	−1.83
Education (*Cannot read & write*)	0.012	0.563	0.02
Household size (*<4**)	−3.186	1.201	−2.65***
Livestock (TLU)	0.771	0.367	2.10**
Land size (ha)	0.255	0.444	0.57
Experience (years)	0.624	0.150	4.14***
Credit (*Yes**)	−2.975	1.769	−1.68
Saving (*Yes**)	−1.590	1.152	−1.38
Weather risk perception (*Yes**)	1.288	1.252	1.38
Livestock market (*Yes**)	2.439	1.186	2.06**
Livestock illness history (*Yes**)	10.270	4745.99	0.001
Insurance history (*Yes**)	1.926	1.416	1.36
Cost of premium (*Yes**)	−6.665	2.689	2.48**
Trust (*Yes**)	−0.318	2769.54	0.01
Accessibility (*Yes**)	−0.482	0.342	0.02
Extension frequency (1*)	0.023	0.234	0.10
Constant	−17.98	2061.108	−0.01
Mills lambda	*0.053*	*0.023*	*2.25***
Rho	*0.913*		
Sigma	*0.058*		

*** and ** Indicate the level of significance at 1 and 5%, respectively. * indicates base category.

capacity. This is probably because households with bigger herd stock could sell large number of livestock and thus generate sound income, which helps them to invest large amount of money for the livestock insurance. This finding is particularly true for the households that offtake livestock at a proper timing where the market has relatively strong demand. This finding agrees with the empirical evidence at Mongolia (Bertram-Huemmer and Kraehnert, 2018), which indicated that the more a household owns herd size, the more it is willing to pay large amount of money for microinsurance.

Similar to the first model estimations, a positive and significant relationship was reported between farmer's paying capacity for IBLI and their past experience with livestock loss. The amount farmers pay for the bid value of IBLI services would increase by 62.4% for every year rise in livestock loss experience. Numerous empirical studies (Aheeyar et al., 2023; Bertram-Huemmer and Kraehnert, 2015) support this result. A farmer's experience with the hazards of livestock loss in drought-prone areas would encourage farmers to adopt alternative solutions such as IBLI and inform their investment decisions, such as buying more size of insurance as a means of exiting the risk.

The robust estimations of the second stage model exhibited a significant and positive relationship between livestock market access and household's capacity to pay for the insurance. Similar to our expectation, a unit increase in market access for the livestock sales would increase the household decision on the amount to pay for the insurance by 2.439 birr. The finding is compatible with findings of previous studies in West Africa (Aina and Omonona, 2012; Aina et al., 2018).

The cost of premium is a significant factor negatively affecting ($P \leq 0.05$) payment amount for livestock insurance. The results indicated that, keeping the influence of other variables constant, an increase in one birr on the IBLI premium cost would decrease the household's WTP the given amounts of bid values for the insurance by 6.66% (Table 6). The high cost of the premium is the most important limiting factor to adopt insurance (Jokhio et al., 2016; Kandel and Timilsena, 2017).

In order to make the premium of the insurance more affordable to farmers, various approaches were recommended by the key informants, one of which is reducing the premium (supply side). A key informant among the IBLI promoter vendors at Fejeje kebele confirmed this line of thought stating:

> *During the first-round premium sales window, largest number of the community purchased the premium, because the project subsidized 75% of the total premium. During the second sale windows, however, the subsidy rate was minimized from 75 to 50% for the purpose of increasing the adaptability of the community to purchase premium even after the project phases out. During the second sales window, the majority could not pay for the insurance, and hence many were requesting the project office to support the premium of an animal subsidy. The cost of the premium is a decisive limiting factor for the farmers. So, the Government should think of substantial premium subsidy.*

This alternative, however, is seemingly unlikely because it requires the government to allocate more budget for premium subsidies, but financial constraints prevent further subsidies from being relied upon. Furthermore, NGO-based subsidies, such as the I4R project, are not sustainable and cannot provide continuous solutions due to their time-bounded nature. Therefore, practical strategies to increase farmers' awareness and WTP (demand side) are strongly recommended.

Overall, the findings showed that pastoralists and agro-pastoralists were aware of the negative consequences that climate change have on their livelihood and production system. They observed that over time, their ability to withstand the negative consequences was diminished by climate change. Throughout the focus group discussions, they underlined that they have no control over climate change. This is mostly because of the recurrent drought in the district, which causes a shortage of water and pasture for their animals. Further, depending on their primary source of income, this effect resulted in livestock death. Worst of all, the effects of climate change made it harder for herders to pay for the insurance necessary to mitigate the rate of cattle mortality from climate change-related causes. As a matter of fact, the poor tailored index-based livestock insurance is a crucial instrument to support the powerless herders and to sustain their livelihoods system in the changing climate.

5 Conclusion and policy recommendations

The study examined the willingness and payout amounts of livestock farmers in Dasenech district, South Ethiopia, to pay for index-based livestock insurance as an alternative climate risk mitigation measure. The data collected through a cross-sectional survey was analyzed using both parametric and non-parametric techniques. During the pilot project implementation years, there was a significant increase in the sales of IBLI and livestock covered by the insurance. The results highlight the importance of insurance schemes for pastoralists and agro-pastoralists, indicating potential interest in IBLI use and potential for scaling up the programs in Ethiopia and similar contexts.

A significant number of district residents, however, are still not paying for microinsurance, indicating the need for further efforts to promote farmer's WTP for insurance coverage. Farmers' WTP for livestock insurance can be increased through a few amendments. The first is to change the pricing and payout methodologies used for premium determination from a region-wide basis to the district level. Therefore, each district might have different premiums that would reflect its level of risks. A district with lower risk will have a lower premium, and farmers in this district might be more interested in purchasing the insurance. Also, rangeland dominance, forage availability, seasonality, and drought history need to be considered. The second requirement is to improve farmers' access to information. According to the results of the double-hurdle model, farmers' WTP had a strong positive correlation with variables such as insurance awareness, training access to farmers, and media access. The awareness creation schemes can include the utilization of different platforms involving facilities, farmers' training opportunities, and campaigns, which provide farmers with information concerning the benefit of insurance and remove their doubts about insurance as an ex-ante risk coping strategy. The third is to educate farmers concerning IBLI. This includes what index-based insurance is, what they get, and what the cost is. When farmers are aware and understand the insurance, they decide to participate in it.

6 Limitations and further research

The study's limitations include limited data and sample size, and its scope only focuses on farmers' willingness to pay for insurance index and premium chargeable. The payout trends observed for IBLI are limited, and a region-wide and longer-term coverage of sales seasons could have improved its comprehensiveness. This study suggests using comprehensive time series data at wider levels for further refinement. If unavailable, a longitudinal study could obtain annual primary data. Future research should cover actuarial issues, projections of drought events, livestock losses, basis risks, prospects of IBLI design and implementation in Ethiopia, and issues of affordable premiums to pay.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

Ethical approval was not required for the studies involving humans because the funding organization did not require it. The studies were conducted in accordance with the local legislation and institutional requirements. Wolaita Sodo University Research Review Board waived the requirement of written informed consent for participation from the participants or the participants' legal guardians/next of kin because Oral consent with respondents was taken before data collection.

Author contributions

TM: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Software, Writing – original draft, Writing – review & editing. DT: Conceptualization, Supervision, Validation, Writing – review & editing. MA: Conceptualization, Supervision, Validation, Writing – review & editing. SB: Software, Supervision, Validation, Writing – review & editing. TF: Funding acquisition, Resources, Supervision, Validation, Visualization, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Climate-smart livestock nutrition in semi-arid Southern African agricultural systems

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Climate change is disrupting the semi-arid agricultural systems in Southern Africa, where livestock is crucial to food security and livelihoods. This review evaluates the bioenergetic and agroecological scope for climate-adaptive livestock nutrition in the region. An analysis of the literature on climate change implications on livestock nutrition and thermal welfare in the regional agroecological context was conducted. The information gathered was systematically synthesized into tabular summaries of the fundamentals of climate-smart bioenergetics, thermoregulation, livestock heat stress defence mechanisms, the thermo-bioactive feed components, and potentially climate-smart feed resources in the region. The analysis supports the adoption of climate-smart livestock nutrition when conceptualized as precision feeding combined with dietary strategies that enhance thermal resilience in livestock, and the adaptation of production systems to the decline in availability of conventional feedstuffs by incorporating climate-smart alternatives. The keystone potential climate-smart alternative feedstuffs are identified to be the small cereal grains, such as sorghum (*Sorghum bicolor*) and pearl millet (*Pennisetum glaucum*) as dietary energy sources, the native legumes, such as the cowpea (*Vigna unguiculata*) and the marama bean (*Tylosema esculentum*) as protein sources, wild browse Fabaceae trees such as *Vachellia* spp. and *Colophospermum mopane,* which provide dry season and drought supplementary protein, minerals, and antioxidants, the non-fabaceous tree species such as the marula tree (*Sclerocarya birrea*), from which animals consume the energy and electrolyte-rich fresh fruit or processed pulp. Feedstuffs for potential circular feeding systems include the oilseed cakes from the macadamia (*Macadamia integrifolia*) nut, the castor (*Ricinus communis*), and Jatropha (*Jatropha curcas*) beans, which are rich in protein and energy, insect feed protein and energy, primarily the black soldier fly larvae (*Hermetia illucens*), and microbial protein from phototrophic algae (*Spirulina*, *Chlorella*), and yeasts (*Saccharomyces cerevisiae*). Additives for thermo-functionally enhanced diets include synthetic and natural anti-oxidants, phytogenics, biotic agents (prebiotics, probiotics, synbiotics, postbiotics), and electrolytes. The review presents a conceptual framework for climate-smart feeding strategies that enhance system resilience across the livestock-energy-water-food nexus, to inform broader, in-depth research, promote climate-smart farm practices and support governmental policies which are tailored to the agroecology of the region.

KEYWORDS

climate-smart agriculture, climate-smart feeding, climate-smart feedstuffs, circular feed use, nutritional bioenergetics, heat stress

1 Introduction

Climate-smart agriculture (CSA) promotes agricultural practices which enhance food security and livelihoods while mitigating and adapting agro-systems to the challenges posed by climate change. This broad climate smart approach seeks to build climate resilience into agricultural systems, to ensure they are equipped to withstand extreme climate-related disruptions (1, 2). It integrates climate-adaptation strategies, and mitigation of the causal factors (3, 4). Maluleke and Mokwena (5), Maluleke and Mokwena (6) indicated that semi-arid Southern Africa faces uniquely adverse climate impacts due to its highly climate-dependent livestock systems. This is compounded by extreme temperatures, prolonged droughts, and erratic rainfall which are common in the region (7). These adverse climatic shifts exacerbate the inherent water scarcity, heat stress on livestock, and reduce forage and food crop yields, significantly compromising established precision livestock nutrition, and may offset the genetic progress in the productivity of livestock and food crops (8, 9). The shortage of high-quality feeds in turn increases producer reliance on less efficient alternatives (10). In the animal body, energy efficiency, and inversely, the heat increment of feeding, and the cellular defences against heat-induced oxidative damage are all strongly influenced by feed quality (11). As stated by Sammad et al. (12), understanding the dietary influences on the animal's thermoregulation, and the impact of heat stress on its health and productivity is crucial to climate-smart feeding. Therefore, addressing climate change impacts on the production of high-quality feedstuffs is crucial to supporting livestock thermal welfare, sustenance of high productivity, reducing greenhouse gas (GHG) emissions, and enhancing systems' sustainability (13).

Millions of people in Southern Africa depend heavily on livestock production for their livelihoods, supporting jobs, economic stability, and food security. The livestock systems in the area are varied and include commercial operations, pastoral systems, and smallholder mixed crop-livestock systems (14). However, the negative consequences of climate change, characterized by extended droughts, unpredictable rainfall patterns, and rising temperatures, pose a growing threat to these systems. The productivity and resilience of livestock are weakened by these climate stressors, which also increase competition for water resources, decrease pasture productivity, and worsen feed shortages (15). Due to their reliance on massive grazing systems and rain-fed agriculture, Southern Africa's semi-arid landscapes are especially susceptible to these effects. For instance, extended droughts in nations such as Zimbabwe, Namibia, and Botswana have resulted in a sharp decline in the productivity of the rangelands, making different ruminant feeding techniques necessary to sustain the livestock. In smallholder systems, the lack of reasonably priced, high-quality feeds during dry seasons frequently leads to decreased output and poor animal health, which fuels poverty cycles.

These difficulties highlight how urgently climate-smart feeding methods adapted to Southern African environments are needed. To address these questions, this review introduces the concept of climate-smart livestock nutrition (CSLN). This involves the selection of feedstuffs based on both nutrient content and thermo-functional properties, and the climate change implications of their production and utilization, to formulate diets that promote thermal regulation, reduce oxidative stress, and minimize GHG emissions, to ensure viable and sustainable feed resources. Climate-smart livestock feeding incorporates novel techniques and feed materials to improve sustainability, resilience, and production (16). Utilizing locally accessible feed resources, such as crop wastes, agro-industrial byproducts, drought-tolerant forage species, and cutting-edge feed technologies such as insect-based proteins and biofortified feedstuffs are possible options to enhance CSLN through climate mitigation by circular feed utilization (17, 18).

To succeed, CSLN requires evidence-driven policies to support research, promote best practices, including the enforcement of regulations on livestock-linked GHG emissions, land, water, and energy use (1). This review explores the biophysical basis and scope for CSLN and outlines a conceptual framework for its implementation in semi-arid Southern Africa, to guide research, farm practices, and policy development.

2 Livestock production, climate change, and climate-smart agriculture

The Earth's atmosphere is primarily composed of nitrogen (78%), oxygen (21%), and trace (1%) quantities of other gases, including argon, carbon dioxide (CO_2), methane (CH_4), and water vapour (19). The phenomenon of rising global average temperatures, or global warming is attributed to the green-house effect of water vapour, carbon dioxide, methane, nitrous oxide and ozone, the greenhouse gases (GHG) which trap heat from the sun, leading to an increase in the earth's surface temperature, to influence the earth's weather patterns (rainfall, temperature droughts), a phenomenon described as climate change (20). Climate-smart agriculture is a concept that is contiguous to the older notion of sustainable agriculture, which emerged in the context of adverse climate change. It provides an over-arching conceptual framework for transforming contemporary agriculture to sustain food security despite climate change (2). The FAO (1) defined CSA as multifaced, to encompass a sustainable increase in agricultural productivity, reduction of climate change vulnerability (adaptation) and GHG emissions (mitigation), while enhancing food security and livelihoods.

Livestock production plays an important role in providing livelihoods and supporting economies at the household, local, national and global scales. Therefore, the sector sits at the center of climate-smart agriculture, for food security (21). The debate on the contribution of livestock production to climate change remains controversial (22). Estimates suggest a contribution of as much as 18% of the GHG emissions into the earth's atmosphere, mostly through enteric fermentation, manure degradation and feed production (10). The GHG emissions depend on the livestock species, systems and practices in relation to inefficiencies, and intensification. Thornton and Herrero (10) reported that approximately one third of the emissions are agronomic (land use and feed production), one-third from manure (nitrous oxide, methane) management, a quarter from enteric methane, and the rest from other livestock-related functions. Herrero et al. (23) estimated that two-thirds of the global emissions come from ruminant systems in the developing world. There is scant data on African livestock systems. However, in sub-Saharan Africa, Graham et al. (24) indicated that typically high emissions per unit product are attributed to low animal productivity, poor animal health, and low-quality feeds. This scenario presents scope to mitigate climate change through efficient feed production and feeding, instead of scaling down production and consumption of the much-needed animal products.

3 Agroecological scope of semi-arid Southern Africa

Climate-Smart Livestock Nutrition (CSLN) is novel in its emphasis on the role of livestock nutrition in mitigating adverse climate change impacts on livestock and the production systems. It seeks to enhance thermal tolerance in livestock, and to reduce greenhouse gas emissions (GHG) from enteric or rumen fermentation, from upstream inputs into feed production such as such fertilizers and irrigation, and from downstream (manure decomposition) emissions. The climate-smart livestock production guidelines of the Food and Agricultural Organization (25) effectively support three primary objectives to anchor the CSLN approach:

- *Adapting to declining feed availability and quality*: Identification of climate resilient crops and varieties, and efficient utilization of feed resources, to address the increasing scarcity and cost of conventional feeds, while maintaining dietary quality.
- *Enhancing livestock resilience to heat stress*: Utilization of dietary ingredients which contain natural mitigants to thermal stress such as antioxidants and electrolytes, to augment body mechanisms for coping with extreme temperatures, and reduce oxidative stress. Additional nutritional interventions include, for example, changing the roughage-concentrate ratio (ruminants) and supplementary dietary fats to ensure adequate energy intake by all livestock despite heat stress.
- *Minimizing the environmental impact:* Develop sustainable feed production, processing and utilization technologies, and increase reliance on circular feed systems, to reduce the ecological footprint of livestock production.

To achieve its objectives in the semi-arid Southern African ecosystems, CSLN demands agro-ecological zone-specific strategies which are tailored to the unique challenges. The agro-ecology is characterized by low and highly variable rainfall (300–600 mm annually), and a mix of soil and vegetation conditions which impose significant constraints to productive, sustainable agriculture. The region increasingly experiences extended dry seasons, with the rain seasons and unpredictable rain, which exacerbates water stress, with high temperatures exceeding 40°C, which further intensify evapotranspiration (26, 27). Climate models project that temperatures will rise faster than the global average, particularly in the low-altitude semi-arid to arid zones, with mean surface warming surpassing global trends in all seasons (28–30). Regions such as the northwest South Africa, Botswana, and Namibia are particularly vulnerable to this accelerated warming (31).

Smallholder farmers in these areas rely on mixed crop-livestock systems, where sheep, goats, and cattle play critical roles in cultural, economic, and food security needs. However, natural rangelands and supplementary crop byproducts, the primary feed resources, are often inadequate during prolonged dry periods. To address these challenges, innovative strategies such as water-saving techniques, forage diversification, and drought-resilient crops are increasingly adopted, which provide potential climate-smart animal nutrition solutions to these harsh conditions.

Livestock systems in semi-arid Southern Africa are particularly vulnerable to the disruptive effects of climate change, particularly rising temperatures, prolonged droughts, and erratic rainfall patterns (5, 7). These changes exacerbate water scarcity, heat stress, and declines in forage and crop yields, negatively impacting livestock nutrition and thermal welfare. The retrogressive effects on precision livestock nutrition compel producers to turn to unconventional feed resources, often inefficient, to sustain or intensify production. This practice, however, risks increasing livestock-generated greenhouse gas (GHG) emissions (32), which demands urgency in adopting strategic interventions such as those advocated by CSLN.

Heat stress poses a particularly significant challenge, with ambient temperatures frequently exceeding the thermal comfort zones of livestock species. For instance, poultry experience stress above 26°C, while cattle are affected when temperatures rise beyond 25–30°C (33–35). Heat stress reduces feed intake, metabolic efficiency, and overall productivity, resulting in financial losses and animal welfare concerns. The CSLN approach addresses these issues by incorporating heat-mitigating strategies, such as diets enriched with antioxidants, electrolytes, and essential nutrients, to enhance livestock thermotolerance.

Beyond thermal resilience, CSLN contributes to broader climate adaptation by ensuring livestock remain productive in sustainable systems despite extreme climatic conditions to support food security and economic stability in vulnerable regions. Effective promotion of CSLN practices requires targeted investments, including funding for the development of heat-mitigating feed additives, integrating them into smallholder and commercial feeding systems, and providing financial incentives to encourage adoption. Additionally, robust support for farmer training programs and extension services is crucial to scaling up CSLN interventions and achieving widespread impact.

4 Conceptual framework for implementing climate-smart livestock nutrition in Southern Africa

A framework for the implementation of effective CSLN should integrate the underpinning principles of nutritional bioenergetics, thermoregulation, oxidative stress, and sustainable feed systems to address the three core objectives: adapting to declining feed availability, enhancing livestock resilience to heat stress, and minimizing environmental impact. A possible conceptual framework is outlined in Table 1.

4.1 Bioenergetics of climate-smart livestock nutrition

Effective climate-smart livestock nutrition solutions require adequate understanding and application of the fundamental bioenergetics. Depending on the species, the thermal homeostasis and nutritional bioenergetics of livestock are profoundly influenced by dietary factors. Diet influences the animal's thermal regulation, including modulation of heat stress as well as defence mechanisms at the molecular, cellular and higher-levels (36). Bioenergetics is therefore, fundamental to the optimum dietary management of the thermal welfare of livestock (37). An array of complex dietary factors is known to influence energy extraction from feeds through both the quantum, and profile of energy

TABLE 1 A conceptual framework for climate-smart livestock nutrition interventions in Southern Africa.

Principles	Concepts	Mechanistic pathways	Impact	Climate-smart interventions	Indicators	References
Bioenergetics	Energy efficiency & heat production	Dietary inefficiencies increase heat production, intensifying heat stress and reducing productivity.	Heat stress from inefficient energy use increases the environmental heat load to limit performance,	Formulate energy-efficient diets with low-heat increment feedstuffs, feedings in cooler parts of the day.	Serum glucose, lactate, rectal temperature.	(10, 13)
Metabolic & hormonal acclimation	Endocrine balance during heat stress	Heat stress alters hormone levels, reducing feed intake and energy balance.	Imbalance in energy availability reduces growth and reproduction.	Manage adverse responses though dietary modifications	Insulin, cortisol, T3, and T4 levels.	(8, 12)
Thermoregulation	Neuroendocrine signaling	Heat stress disrupts neuroendocrine signals affecting metabolism and behavior.	Altered signaling reduces feed intake and changes metabolic responses.	Manage adverse responses though dietary modifications	Dopamine, norepinephrine, cortisol levels.	(7, 10)
Oxidative stress	Reactive oxygen species (ROS) control	Heat stress elevates ROS levels, causing cellular oxidative damage.	Oxidative damage decreases immune responses and overall productivity.	Supplement diets with antioxidants (vitamin E, curcumin) to neutralize ROS and reduce oxidative stress.	ROS levels.	(9, 13)
Heat shock response	Heat shock proteins (HSPs)	HSPs protect cells from heat-induced damage by stabilizing protein structure.	Reduced HSPs increase susceptibility to cellular damage and stress.	Nutritional approaches to support HSP regulation using supplements to enhance resilience to heat stress.	HSP70 levels, HSF-1 activity.	(11, 18)
Epigenetics	Epigenetic modifications for thermal tolerance	Heat triggers DNA methylation and histone protein modifications to influence gene expression.	Epigenetic alterations can either enhance or reduce stress resilience.	Use epigenetic markers in selective breeding for thermal tolerance; methyl donors such as choline, folate, betaine in diets to modulate gene expression.	DNA methylation patterns, histone acetylation levels.	(1, 10)
Nutrigenomics	Nutrient effects on gene expression	Nutrients regulate genes which control stress tolerance, metabolism, and immunity.	Improves feed efficiency, heat resilience, and immune function.	Supplement with selenium, omega-3 fatty acids, and antioxidants to modulate stress-related gene expression.	Gene expression levels (HSPB8, SERPINH1), antioxidant enzyme activity.	(7, 8)
Nutrigenetics	Genetic variation & dietary responses	Genetic polymorphisms affect nutrient metabolism and thermal tolerance	Inefficient nutrient absorption or metabolism due to genetic variation can reduce performance in heat stress.	Tailor diets to match genetic profiles (precision feeding) to improve nutrient efficiency and stress resilience.	Nutrigenetic markers for nutrient metabolism and heat resilience.	(10, 12)
Sustainable feeds	Climate-smart feedstuffs	Climate change reduces conventional feed availability, increasing the use of alternative, sustainable feed sources.	Decreased feed availability leads to reduced productivity and higher methane emissions.	Use insect feed, climate-resilient forage crops, and alternative protein sources to lower greenhouse gas (GHG) emissions and improve resilience.	Feed quality (protein, fiber content), methane emissions.	(1, 17)
Antioxidant defence	Exogenous antioxidants	Bioactive dietary compounds reduce oxidative stress and enhance cellular protection.	Elevated oxidative stress reduces animal health, productivity, and immune function.	Use of supplements to enhance antioxidant defences.	Plasma antioxidant levels, oxidative stress biomarkers.	(9, 13)
Water-electrolyte balance	Hydration & electrolyte homeostasis	Heat stress accelerates fluid loss and causes electrolyte imbalances	Dehydration and imbalances lead to reduced productivity and health.	Supplement electrolytes (Na, K, Cl) to maintain hydration and heat tolerance.	Plasma osmolality, Na+, K+, Cl − levels, feed intake, body weight and feed efficiency	(3, 12)

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substrates, and the intermediates, as they flow into central metabolism, to determine the overall dietary energy efficiency, and inversely, heat production (38). These bioenergetic interactions are summarized in Table 2. Therefore, climate-smart feed characterization and diet formulation should prioritize the influences on energy consumption and efficiency, and the associated heat production, in relation to heat stress, and its effect on the animal's biochemical and physiological functions which determine productivity. In semi-arid Southern Africa, livestock are frequently subjected to environmental stresses such as heat and feed scarcity, factors which can drastically change their energy needs and utilization (15). For example, increased thermoregulation due to heat stress can increase maintenance energy demands, reducing the energy available for growth, reproduction, or milk production.

4.2 Metabolic and hormonal acclimation to a hot environment

Reduced feed intake is the direct mechanism through which heat stress affects production and reproduction, coupled with altered endocrine status, increased maintenance requirements, decreased rumination and or nutrient absorption (39). These mechanisms contribute to a net decrease in nutrient/energy assimilation. For example, lactating heifers lose body weight during periods of extreme heat stress, which is at least partially explained by a drop in energy intake, coupled with an increase in energy expenditure for maintenance (40).

Hormones are linked to the body's acclimatory reaction to heat stress (39). These include growth hormone, prolactin, thyroid hormones, glucocorticoids, and mineralocorticoids. The thyroid hormones, T4 and T3, have drawn the most interest because they constitute a key acclimatization mechanism. Mammals that have evolved to warmer temperatures are known to follow the pattern of decreased endogenous thyroid hormone levels during heat acclimation as a means of reducing endogenous heat generation (41). Research shows that insulin is also involved in acclimation with animals under heat stress showing greater insulin levels, even if they consume less feed. The function of insulin in inducing heat shock proteins may partially explain this conundrum (42). For example, HSP70 expression is positively correlated to circulating insulin levels (43), and adaptation to hypoxia requires both HSP90 and insulin responses (44).

The neurotransmitters dopamine and norepinephrine are involved in modulating thermoregulation during heat stress (45). They influence the physiological and behavioral responses to thermal stress, which makes them relevant to the overall stress management in livestock. Understanding neuroendocrine pathways is therefore essential for developing effective climate-smart feeding strategies. By targeting these pathways, it is possible to optimize feeding practices to enhance animals' resilience to heat stress (34). The central nervous system plays a major role in hormone regulation. The hypothalamic–pituitary-thyroid axis, the sympathetic-adreno-medullary axis, the hypothalamic–pituitary–adrenal axis (HPA), and the hypothalamic–pituitary-gonadal axis can all be affected by heat stress. The primary neurosecretory systems triggered by stress include the HPA and sympathetic-adrenal-medullary (SAM) system, among others (46, 47). As reported by Beede and Collier (48), when animals are thermally challenged, the endocrine system, a vital component in the coordination of metabolism, undergoes significant modifications. Collier et al. (39) stated that the hypothalamic–pituitary–adrenal axis represents a crucial element of the body's acclimatory reaction to heat stress while the thyroid hormones, specifically T3 and T4, are essential for animals' proper growth, differentiation, and metabolism. They are essential for controlling body temperature, energy intake, and thermal metabolic adaptability (49). Elevated ambient temperature dramatically diminishes T3 secretion while augmenting T4 synthesis in chickens (50). Yousef and Johnson (51) identified a synergistic impact between the decrease in thyroid hormones and the decreased level of growth hormone in plasma which aids the body's urge to minimize heat production. Thyroid atrophy and diminished secretory function, and other thyroid-related conditions may be direct impacts of heat stress (52).

TABLE 2 Bioenergetics, heat stress, and thermoregulation in livestock.

Bioenergetic factors	Thermal responses and mechanisms	References
Thermal stress	*Climate-induced heat stress*: Increased frequency of extreme temperatures in prolonged heatwaves negatively affects livestock welfare and productivity.	(39, 40)
	Oxidative stress: Heat stress enhances reactive oxygen species (ROS) production, leading to cellular lipid peroxidation and protein denaturation, which impair growth; mitochondria are primary ROS sources.	(61, 63)
	Altered energy metabolism: Elevated maintenance energy demands coupled with decreased feed intake and nutrient absorption compromise growth under heat stress.	(40)
Neuro-endocrine regulation	*Neuroendocrine responses*: Dopamine and norepinephrine modulate stress responses via the hypothalamic–pituitary–adrenal (HPA) axis and sympathetic-adrenal-medullary (SAM) systems.	(45)
	Endocrine responses: Reduced levels of T3 and T4 hormones lower heat production; increased insulin promotes heat shock protein (HSP) expression, enhancing stress adaptation.	(39, 42)
Molecular defences	*Heat Shock Proteins (HSPs)*: HSPs act as molecular chaperones to facilitate proper protein folding and prevent aggregation during thermal stress; HSF-1 regulates HSP expression and serves as a biomarker for resilience.	(67)
	Antioxidant defense systems:	(78)
	Enzymatic: Key enzymes (SOD, catalase, glutathione peroxidase) convert ROS into less harmful molecules, protecting cells from oxidative damage.	
	Non-Enzymatic: Plant-derived and synthetic bioactive dietary compounds such as glutathione, vitamin E, polyphenols, and flavonoids neutralize ROS and support cellular repair, mitigating oxidative stress.	(74, 76, 87, 205)

One of the primary hormones involved in the stress response is cortisol which primarily supports gluconeogenesis by promoting protein metabolism (53), which turns proteins into amino acids. Sejian and Srivastava (54) pointed out that in the liver, muscle, and adipose tissue, the cortisol produced by the adrenal cortex promotes the breakdown and release of glucose, amino acids, and fat. Almost every biological function that is impacted by stress is regulated by cortisol, including behavior, metabolism, immunological response, and reproduction. The goal of these hormonal reactions is to increase the capacity to withstand stress. Elevated blood cortisol levels due to high temperatures have been reported to slow down the rate at which heat is produced metabolically (54, 55).

Somatostatin is stimulated by corticotropin-releasing hormone, which may be a major mechanism explaining heat-stressed animals' decreased thyroid and growth hormone levels (56). Glucocorticoids in dairy cattle fall during acclimatization at high temperatures and were lower in animals that had been thermally acclimated than in controls (57, 58). Heat stress stimulates the hypothalamic axis, which reduces animal feed intake by upregulating the production of adiponectin and leptin as well as the expression of their receptors (59). The receptor and expression of the Neuritin B gene could be enhanced by the thermal challenge (60).

4.3 Oxidative stress and cell damage

A biological system constantly produces free radicals, some of which are necessary for physiological functions. The mitochondria are the primary location of aerobic cellular reactive oxygen species (ROS) generation and use more than 90% of the cellular oxygen in undisturbed cells (61, 62). Enzymatic oxidase reactions and the endoplasmic reticulum's microsomal systems produce ROS (63). When the body produces excessive ROS, lipid peroxidation occurs, which negatively impacts organelles and cell membranes. Superoxide anions, hydrogen peroxide, and hydroxyl radicals are examples of reactive oxygen species that are produced in the mitochondria and function as signaling intermediaries (64).

4.3.1 Heat shock proteins (HSPs)

Heat shock proteins (HSPs) are molecular chaperones which protect cells from heat-induced damage by aiding in protein folding and preventing aggregation (65). These proteins are upregulated in response to various forms of stress, including heat stress, and play a critical role in cellular protection and recovery (66). Heat Shock Factor-1 (HSF-1) is a key regulator of the heat shock response. It orchestrates the transcription of heat shock proteins by binding to heat shock elements (HSEs) in the DNA, thus initiating the cellular stress response (67). In climate-smart feeding, monitoring HSP levels and analyzing HSF-1 activity or its binding to HSEs can serve as indicators of an animal's capacity to activate protective mechanisms against thermal stress (68).

4.3.2 Antioxidant enzyme defence systems

Under normal conditions, antioxidant enzymes such as catalase, glutathione peroxidases, peroxiredoxins, and superoxide dismutases constantly remove produced ROS (64). When reactive oxygen species are overproduced under stressful situations, hydrogen peroxide is released, creating oxidative stress. This can overload the antioxidant defense system and lead to an imbalance in the redox system (62, 69–71). In addition to increasing plasma corticosterone levels in chickens, stress activates the hypothalamic pituitary adrenal axis (72).

Exogenous and endogenous antioxidants in biological antioxidant defense systems are divided into enzymatic and non-enzymatic categories, which include ROS/RNS scavengers, transition metal chelators, oxidative enzyme inhibitors, and antioxidant enzyme cofactors (73). Low molecular weight antioxidants and antioxidant enzymes are the two main categories of antioxidants. Glutathione peroxidase, catalase and superoxide dismutases and other enzymes are among the most significant antioxidants. Glutathione, flavonoids, carotenoids, vitamin E, vitamin C and other antioxidants are among the most significant low molecular weight antioxidants. These two primary antioxidant systems are crucial in preserving the equilibrium between antioxidant and pro-oxidant agents while reducing oxidative stress (74). Antioxidants work by directly scavenging oxidizing radicals and allowing organisms to repair their damaged biomolecules. Under extreme stress, their activities are restricted (71, 75, 76). A class of proteins called antioxidant enzymes, also known as metalloproteins, catalyze the conversion of reactive oxygen species (ROS) and/or their metabolites into more stable, generally less dangerous species. Antioxidant enzymes are a crucial defensive mechanism against oxidative stress caused by reactive oxygen species (ROS), which damages cell components (77).

While non-enzymatic antioxidants include peroxide decomposers, oxidative enzyme inhibitors, metal chelators, singlet oxygen quenchers, and/or ultraviolet radiation absorbers and enzymatic antioxidants play a protective role by breaking chains of free radicals and scavenging them (73). Superoxide dismutase was the first line of defense against free radicals and maintained cellular redox equilibrium among the potential reactive oxygen species scavengers (78). The SOD is therefore essential for the early stages of defense against ROS-mediated oxidative damage. By facilitating the transformation of superoxide into oxygen and hydrogen peroxide, SOD is an essential component of the defense against free radicals.

Because aerobic organisms produce this enzyme broadly, it is an essential part of the first line of defense against oxidative stress (78). There are three different isoforms of SOD: extracellular SOD3, mitochondrial SOD2, and cytoplasmic SOD1. Most eukaryotic cells have SOD2 and SOD3, with SOD3 being the main isoform identified in the cardiovascular system (79). Nuclear genes encode manganese superoxide dismutase, or SOD2, an antioxidant enzyme. Mutations or disruptions in SOD2 function have been linked to changes in the structure of the mitochondria seen in diseases such as heart failure (80). Reduced SOD2 levels cause ROS to build up and then excessive 4-hydroxynonenal synthesis in the mitochondria (64).

4.3.3 Superoxide dismutase activity and gene expression

Seasonally appropriate feeding, providing feeds high in fiber and fats, supplementing with vitamins and minerals, and offering cold drinking water are some of the dietary changes that promote activities of superoxide dismutase enzyme (68). The orange-yellow lipophilic polyphenolic compound curcumin is extracted from the rhizome of herbs. Its antioxidant and anti-inflammatory qualities have led to its recognition for its important role in the treatment and prevention of cardiovascular diseases (81). Through a variety of methods, the bioactive substance curcumin protects the cardiovascular system from OS. In order to attenuate OS, lower ROS levels, and restore cardiac SOD levels, two important processes implicated are the activation of the PI3K-Akt survival pathway and the SIRT1-FoxO1 pathway (82). Owing mainly to its antioxidant qualities, salvianolic acid, a naturally occurring polyphenolic molecule obtained from *Salvia miltiorrhiza*, demonstrated noteworthy preventive actions against cardiovascular diseases. Salvianolic acid has been shown in numerous studies to be able to postpone the onset of ischemia in animal models of MI by increasing angiogenesis, decreasing infarct size, and enhancing post-infarction contractile performance (83).

In order to coordinate cellular and whole-animal metabolism, gene networks both inside and across cells and tissues react to external heat loads exceeding the thermoneutral zone by sending out intra-and extracellular signals. In Vrindavani cattle (*B. indicus* X *B. taurus*), heat stress response genes (SERPINH1, DNAJ4, FKB4, HSPB8 and HSPH1) were up-regulated at a greater fold change (244). High ambient temperature modulates heat shock protein genes to shield the cells and proteins from a changed metabolism. Induced heat stress causes such changes in physiologic parameters that modify the neuroendocrine system (84). Elayadeth-Meethal et al. (85) investigated the differential expression and molecular mechanism of the HSPA1A gene in dwarf Vechur cattle, Kasaragod cattle, and crossbred cattle in an experimental field context. They concluded that HSPA1A is a possible candidate gene for heat tolerance. The potential for improving thermotolerance through manipulation of the genes regulating HSF1 expression and evaporative heat loss in cattle is suggested by the variation in evaporative heat loss among animals and the crucial role that (heat shock transcription factor 1) HSF1 plays in coordinating thermal tolerance (86).

4.3.4 Exogenous, non-enzymatic antioxidants

Exogenous antioxidants are abundantly found in natural plants and primarily consist of polyphenols and natural flavonoids. Supplementation with exogenous antioxidants exerts potent antioxidant effects by engaging various signaling pathways. These pathways include augmenting the antioxidant capacity of endogenous antioxidant systems, thereby reducing OS, inhibiting ROS production, consequently restraining OS, and activating antioxidant signaling pathways that counteract OS (87).

5 Functional compounds in climate-smart feedstuffs

The functional compounds in feeds are the bioactive molecules that have specific physiological or health effects beyond nutrition (88). In the context of thermal stress and oxidative cell damage, there are compounds that help animals cope with heat stress, in support of the internal antioxidant defences, immune responses, and overall biochemical and physiologic resilience to heat stress (245). Climate-smart feeds may contain an array of functional compounds. The natural functional compounds which may be present in climate-smart feedstuffs are indicated in Table 3. To operationalize these solutions to enhance livestock's health, productivity, and resilience in the face of climate stress, feeding plans need to be modified to fit the resource limitations and production systems of semi-arid Southern Africa. Examples of specific or targeted interventions include the following;

- Antioxidant supplementation: Supplementing with natural antioxidant-rich feedstuffs, such as sorghum bran and sunflower meal, can help reduce the oxidative stress brought on by exposure to heat. These dietary components can be added to concentrates designed to meet animal demands or utilized in silage.
- Phytogenic supplements: To improve gut health and lower oxidative stress, livestock diets can include locally accessible plants with multifunctional bioactive components as feed additions. The phytogenic additives can be combined with crop residues or tree fodder after being processed into meal or extract form.
- Probiotics and prebiotics: Smallholder farmers can use fermented feed technology to add healthy microorganisms to livestock diets, to enhance gut health and nutrient absorption. Fermenting waste grains or grain crop byproducts with supplementary molasses can be an inexpensive way to distribute probiotics.
- Integrated feeding systems: In smallholder systems, functional compounds can be incorporated into domestic feed formulations by employing locally accessible resources. For example, cattle could be supported during the dry season by combining crop residues enriched with neem leaf powder and treated with antioxidants. To target high-value production systems such as dairy or poultry farms, feed manufacturers could create pre-mixed functional ingredient supplements. To cut farmers' expenses, these might be provided via cooperatives.
- Policy and capacity building: Funding for farmer education programs on processing methods and the advantages of functional compounds is necessary for successful implementation. The feed industry and extension agencies must work together to guarantee that these compounds are affordable and available for a variety of farming methods.

6 Climate-smart feed resources in semi-arid Southern African ecosystems

In the semi-arid regions of Southern Africa, developing sustainable, climate-smart livestock feeding systems is imperative to mitigate severe environmental constraints such as drought, heat stress, and low soil fertility. Climate-smart feedstuffs are those which are cultivated or exploited from the wild, which meet the climate-smart definition, they comply with the agroecological principles of sustainability, productivity and nutritional quality, with least energy, chemicals, and water input (246). The cultivation or wild exploitation of such feed resources should minimize upstream (irrigation, pesticides, fertilizer) greenhouse gasses (mitigation), and promote the most productive, ecologically adapted, climate resilient or drought-tolerant species and varieties (adaptation) (247). Though research on climate-smart feed resources is still limited and fragmented, several promising candidates are emerging, which can be produced or exploited on a large-scale for viable value chains. Strategic incorporation of these feeds, ranging from the drought-tolerant native grain cereals and legumes to biofuel or pharmaceutical oilseed cakes, the wild or cultivated browse trees and the fruit

TABLE 3 Dietary chemical defences against thermal stress and oxidative cell damage.

Functional Compound	Examples	Role and application	References
Antioxidants	Vitamin E Selenium Polyphenols Flavonoids	• Neutralize free radicals generated during oxidative stress, protecting cells from damage. • Can be naturally present in feeds, or as synthetic supplements.	(74, 76)
Electrolytes	Sodium Potassium Magnesium Chloride Bicarbonate Trace minerals	• Maintain fluid balance and prevent dehydration under heat stress. • Regulate the acid–base balance of the internal environment. Which can be disrupted during thermal stress, ensuring proper muscle and nerve function. • Supplementing electrolytes in feed or water helps animals maintain homeostasis during periods of high heat.	(39, 233)
Fatty acids	Omega-3 fatty acids	• Anti-inflammatory properties that reduce cellular damage and inflammation caused by oxidative stress during heat exposure. • Modulate the immune response and improve overall health and productivity under thermal stress.	(234)
Amino acids	Methionine, Taurine Glutamine	• Higher requirement for essential amino acids, primarily methionine, to compensate for the increased protein synthesis during cellular repair after heat related oxidative damage. • Precursors for antioxidant molecules (e.g., glutathione) that protect cells from oxidative damage caused by heat stress. • Taurine is particularly important in maintaining cellular integrity and hydration under stress.	(42)
Carotenoids	Beta-carotene Astaxanthin Lutein	• Beta-carotene helps in removing ROS, protecting cells from oxidative damage. • Astaxanthin, found in microalgae, is a potent natural antioxidant, protecting cell membranes from peroxidation under heat stress. • Lutein supports eye and skin health, to improve thermal resilience.	(61)
Vitamins	Vitamin C Vitamin A	• Vitamin C is a potent antioxidant that removes ROS in tissues exposed to high temperatures. • Vitamin A supports the immune system and protects against oxidative damage in epithelial tissues, improving overall animal health under stress conditions.	(76)
Catalytic minerals	Zinc, Copper, Manganese	• Trace minerals – co-factors for enzymes involved in antioxidant defense systems. • Zinc is a co-factor for superoxide dismutase. • Manganese supports mitochondrial function, reducing oxidative damage in cells.	(78, 233)

byproducts, and single cell (microbial) protein presents ample opportunity for CSLN (89). A selection of the feed resources which have attracted research attention for potential integration into climate-smart livestock nutrition in semi-arid Southern Africa are profiled in Table 4. The challenges in research are to expand the existing matrix of (conventional) feedstuffs by identifying, and characterizing (nutrients, bioactive compounds) climate-smart alternatives, to facilitate least cost, climate-smart formulation of diets for different livestock (90).

6.1 Local production and applicability of climate-smart livestock feeds in semi-arid Southern Africa

6.1.1 Small cereal grains

In the advent of climate change, the traditional small cereal grains may become dietary energy options, despite their previous displacement as staple food crops by improved, maize hybrids. Of the small grains, sorghum (*Sorghum bicolor*) and Pearl millet (*Pennisetum glaucum*) seem to be the most suitable candidates. They are tolerant to heat, drought and low soil fertility, and yield reasonably well under such adverse conditions. Apart from the organic and mineral nutrients, the small grains contain many functional nutrients. Sorghum contains the flavonoids luteolin, kaempferol, quercetin, catechin and the phenolic acids such as ferulic acid, caffeic acid, vanillic acid, p-coumaric acid (91, 92), compounds which help reduce oxidative stress in heat-stressed livestock (78). Pearl millet is rich in the flavonoids tricin and acacetin, as well as phenolic acids such as vanillic and salicylic acids (93).

6.1.2 Grain legumes

In the context of CSLN, two native grain legumes seem to be the most eligible alternative dietary plant protein sources to complement the small cereal grains for livestock feeding in semi-arid Southern Africa. The Cowpea (*Vigna Unguiculata*) is widely cultivated, highly

TABLE 4 Profile of representative potential climate-smart in semi-arid Southern African.

Feed category	Keystone candidate climate-smart feedstuffs	Climate-smart attributes	Bioactive compounds	Limitations	Recommended processing	Sources
Small cereal grains	Sorghum (*Sorghum bicolor*), grain	Drought-tolerant, comparatively high yield potential, suitable for low-input agriculture; high energy	Flavonoids, phenolic acids	Low lysine, tannins	Soaking, sprouting, cooking, fermentation.	(91, 235)
	Pearl Millet (*Pennisetum glaucum*), grain	Adapted to dry conditions, high energy, minerals	Phenolic acids	Phytates	Phytase	(93)
Cultivated grain legumes	Cowpea (*Vigna unguiculata*), grain	Tolerant to drought, high protein, enhances soil fertility	Flavonoids, phenolic compounds	Trypsin inhibitors, lectins and other antinutrients	Cooking, soaking, sprouting	(94–96)
Wild grain legumes	Marama Bean (*Tylosema esculentum*), grain	Adapted to arid environments, high protein, high oil (energy) content	Phenolic acids, phytosterols, flavonoids	Trypsin inhibitors and other antinutrients	Heat treatment	(97)
Roots and tubers	Cassava (*Manihot esculenta*) roots	Drought tolerant, high energy	Cyanogenic glycosides	Cyanogenic glycosides (leaves, peels of raw tubers)	Peeling, sun drying, fermentation, cooking	(99, 100)
Wild trees	*Vachelia* spp., pods, twigs, leaves	Drought-resistant, legume, dry season and drought feed, protein-rich, minerals	Polyphenols, flavonoids, terpenoids, glucosinolates, carotenoids	Tannins	Soaking, chemical treatments (lime, sodium bicarbonate)	(101, 102)
	Colophospermum mopane, pods, young twigs, leaves	Drought-tolerant, dry season and drought feed, legume, protein-rich, minerals	Polyphenols	Tannins	Soaking, chemical treatments (lime, polyethylene glycol, fermentation)	(101, 102)
	Marula (*Sclerocarya birrea afra*), fruit pulp	Drought-resistant, high in carbohydrates, vitamins, and antioxidants	Vitamin C, phenolic compounds tocopherols (Vitamin E)		Drying, fermentation	(236)
Food nut oilseed cakes	Macadamia (*Macadamia integrifolia*), seed oil cake	High protein, essential fatty acids, high energy	Monounsaturated fats, antioxidants (vitamin E, polyphenols)	High fiber for mnogastrics		(109, 110)
Pharmaceutical oilseed cakes	Castor Bean (*Ricinus communis*) seed oil cake	Drought-tolerant, high protein, essential fatty acids, high energy		Ricin	Heat treatment, fermentation	(111)
	Prickly Pear (*Opuntia ficus-indica*), seed oil cake	Drought-tolerant, protein and energy rich	Antioxidants (betalain pigments, vitamin C), electrolytes	Oxalates	Drying, soaking, water leaching, chemical treatment (lime)	(237, 238)
Biofuel oilseed cakes	Jatropha (*Jatropha curcas*) seed oil cake	Drought-tolerant, high protein content, essential fatty acids		Phorbol esters	Fermentation, heat treatment	(112)
Forages – grass	Napier Grass (*Pennisetum purpureum*)	High yielding, drought-tolerant, suitable for various soil types			Drying, fermentation	(239)
Forages-xerophytes	Spineless Prickly Pear (*Opuntia ficus-indica*) cladodes & waste fruit	Drought-tolerant, high-water content, vitamins, minerals	Antioxidants (betalain pigments), electrolytes	Oxalates	Drying, soaking, water leaching, chemical treatment (lime)	(240)
Insect feed	Black Soldier Fly Larvae (*Hermetia illucens*)	High protein, high energy (full-fat), waste management	Essential amino acids, fat (energy), antimicrobial peptides		Drying, defatting	(120–122)
Microbial derived feeds	Phototrophic algae (e.g., *Spirulina, Chlorella*)	High protein source, rich in carotenoids and polyphenols, omega-3 fatty acids	Carotenoids, polyphenols, DHA, EPA vitamins (B12)	High production cost, scalability challenge, Allergenicity	Drying	(124–126)
	Yeasts (e.g., *Saccharomyces cerevisiae*)	High protein, antioxidants, beta-glucans, ergosterol, reduces methane emissions in ruminants, B-vitamins	Beta-glucans, ergosterol, mannan-oligosaccharides, antioxidants, B-vitamins (B1, B2, B6, B12)	Strain-specific responses, high production cost, Risk of digestive upset if used in excess	Fermentation	(127–129)
Cereal grain processing byproducts	Brewers' spent grains	Circular feed use	B-vitamins, polyunsaturated fatty acids, phenolic acids, antioxidants	Mycotoxins		(130–132)
	Maize milling byproducts	Circular feed use		Mycotoxins, variable quality		(133)
	Distillers' dried grains	Circular feed use		Mycotoxins, variable quality		(134–136)

climate and edaphically adaptable, rich in protein, starch, minerals, and the B-group vitamins (94–96). The Marama bean (*Tylosema esculentum*) is a wild, and widely endemic in the region, is protein-rich, drought-resistant, but largely neglected perennial legume (97). In addition to the high protein content, the marama bean is rich in phytochemicals such as phenolic acids, phytosterols, flavonoids, behenic acid and griffonilide, with carbohydrate content in the tubers (97). However, typical of the genus among other undesirable attributes, these leguminous feedstuffs contain high levels of trypsin inhibitors and other toxic antinutrients, which necessitate processing to optimize their nutritional benefits (94).

6.1.3 Roots and tubers

There are a range of climate-resilient indigenous root/tuber crops, many of which are excluded due to the feed-food competition. In this regard, Cassava (*Manihot esculenta*) is an outstanding climate-smart alternative to maize for livestock feeding in semi-arid Southern Africa. Yet to find a firm footing in the region's agriculture and the food chains, Cassava is drought and heat-tolerant and grows well in poor soils (98). Compared to maize grain, cassava has a higher root biomass and yields more starch at a lower input cost (99, 100). However, along with the leaves, the root periderm contains cyanogenic glycosides, particularly linamarin and lotaustralin, which remain toxic if not properly processed (99).

6.1.4 Browse trees and byproducts

Ruminants in Southern African rangelands browse on many leguminous tree species such as, among others, *Piliostigma thonningii*, *Dichrostachys cinerea*, *Colophospermum mopane*, and *Vachellia karroo*, from which they consume the high-protein pods, twigs, and leaves, mostly during the dry season. These components can alternatively be harvested and processed into bush meal, and similarly for dry-season or drought feeding (101, 102). Bush meal also contains a range of bioactive compounds, including phenolics and flavonoids, with high tannin levels that inhibit protein digestibility. The tannins can be neutralized by supplementary polyethylene glycol (PEG) or can be reduced through soaking and ensiling (103, 104). With proper treatment, bush meal can be a sustainable, climate-smart feed.

A wild, non-legume fabaceous tree feed resource which is abundant in the ecosystem is the Marula (*Sclerocarya birrea* subsp. *Caffra*). Endemic to much of sub-Saharan Africa, the Marula tree produces fruits which are rich in vitamins, amino acids, carbohydrates, organic acids, and polyphenols (105). Livestock consume the fresh fruit's pulp or its processed byproducts from traditional brewing, such as ensiled or dried pulp. The Marula fruit has a high sugar content which provides dietary energy. The dried pulp preserves most of the essential nutrients, while fermentation enhances the digestibility and introduces beneficial probiotics (106). Climate models suggest increased Marula abundance, which reinforces its potential role as a significant climate-smart feed (107).

6.1.5 Oilseed cakes from climate-resilient plant species

Oil extraction byproducts from a range of wild or cultivated climate-resilient plant species which are common in semi-arid regions, where they have attracted attention as alternative protein and energy options for livestock feeding. Oil cake from the *Macadamia integrifolia* nut contains as much as 19.5% crude protein and is a cost-effective source of dietary energy (108, 109). However, its high fiber content (up to 25%) limits its inclusion in monogastric livestock diets to avoid depressed feed intake and nutrient digestibility (110).

The pharmaceutical oil cake from the castor bean *(Ricinus communis)* is rich in protein and energy, but contains toxins, primarily ricin. Ricin and its poisonous derivatives can be destroyed by moist heat treatment or low pH fermentation (111). The biofuel byproduct from *Jatropha* (*Jatropha curcas*) beans is high in protein and energy but contains toxic phorbol esters. The phorbol esters can be detoxified by heat treatment or fermentation (112).

6.1.6 Forage crops

Two species stand out as potential climate-smart forage resources in the region. One of these is Napier grass (*Pennisetum purpureum*), a high-yielding, drought-tolerant forage crop suitable for semi-arid regions (113). The other one is the Prickly pear (*Opuntia ficus-indica*), which, despite classification as an invasive plant, plays a significant role in supporting rural livelihoods (114). Endemic to arid regions, the Prickly pear is increasingly cultivated for its fruit or forage. The water-rich leaves (cladodes) are the primary livestock forage, which along with the byproducts, namely waste fruit and seed oil extraction cake can be used as feed for livestock (115, 116). Prickly pear feed products are rich in energy, protein, antioxidant flavonoids and phenolic acids, and betalain pigments (betacyanins and betaxanthins) that express antioxidant and anti-inflammatory properties (115, 117). However, the products contain tannins and phytate, which may require processing (118, 119).

6.1.7 Insect feed

The use of alternative, comparatively inferior protein sources such as native legumes for livestock feeding could undermine the formulation of precision diets, and increase the need for expensive supplementary animal protein, such as fishmeal. However, fishmeal is also threatened by climate change and overfishing. Insect feed, particularly the Black Soldier Fly larvae (*Hermetia illucens*), is emerging as a viable alternative (120–122). Black Soldier Fly larvae contain high levels (40–44%) of crude protein, with advantage of efficient, eco-friendly production (120, 123).

6.1.8 Microbial feedstuffs

Phototrophic algae (124–126) and yeasts (127–129) are potential climate-smart feed resources. Subject to the cost, microbial feedstuffs carry the advantage of efficient production of protein in controlled environments, with minimal land and water input, and low environmental impact. In addition to protein, microalgae are rich in carotenoids and polyphenols, which neutralize ROS and mitigate oxidative damage (124, 125). Yeasts produce antioxidants and beta-glucans and ergosterol, which support immune functions and reduce oxidative cell damage (128).

6.1.9 Cereal grain processing by-products

Brewers' spent grains contain 20–30% crude protein and are rich in B-vitamins such as thiamine and riboflavin (130). They also contain high levels of phenolic acids (130, 131). However, they may be contaminated with mycotoxins (132). Maize milling byproducts (bran, germ meal, gluten feed or meal, hominy chop) contain variable (8–23%) crude protein, are noted for their phenolic compounds such as ferulic acid, which offers antioxidant benefits (133). However, these byproducts may also contain mycotoxins, necessitating careful management to ensure feed quality. Distillers' dried grains are a byproduct of ethanol production with a high (25–35%) crude protein content and are rich in diversely bioactive compounds (134–136).

6.1.10 Circular feed systems

Similar to circular food systems (137), circular feed systems are more sustainable and reduce the environmental footprint. Examples of the climate-smart feedstuffs in such circular systems include the oilseed cakes, cereal grain processing byproducts and insect feeds efficiency (138).

Circular feed systems emphasize recycling and reusing locally accessible feedstuffs to cut waste and boost system resilience for sustainable feeding of livestock. This strategy fits into CSLN, especially in semi-arid areas where resource limitations and feed scarcity are most intense (139). For example, brewers' spent grains, oilseed cakes, and fruit pulp are agricultural and agro-industrial by-products that can be recycled into nutritionally balanced livestock meals. While technologies such as composting organic waste or raising insects such as Black Soldier Fly larvae turn waste streams into high-quality protein feeds, dual-purpose crops such as maise and sorghum supply grain for human use and leftovers for livestock feeding (140). Furthermore, livestock dung can improve soil quality, promoting the development of fodder crops and maintaining a closed-loop nutrient cycling system.

Crop residues, by-products, and organic waste are examples of locally accessible resources used as major inputs in this system. To increase feed value and reduce spoilage, these resources are processed using technologies such as fermentation, urea treatment, and silage production. While feedback loops ensure that animal waste, including manure, is returned to the land to increase forage production and promote sustainable agriculture, the outputs are nutrient-dense, inexpensive feeds that satisfy cattle's energy and protein needs.

7 Feed additives and supplements

Where the novel diets lack adequate biofunctional compounds to achieve the climate-smart objectives, a range of synthetic or microbial or plant-derived products can be used. There is a range of feed additives and supplements that enhance animal well-being and performance. These can be natural plant extracts, or synthetics (141). Candidates for adoption in CSLN are described in Table 5.

7.1 Methane suppressors

The livestock gut fermentation process produces significant greenhouse gasses, particularly methane, which plays a major role in climate change. A range of additives which include probiotics, exogenous enzymes, plant metabolites and fodder trees, organic acids, and other microbes reduce methane emission (142).

7.2 Heat stress modifiers

Heat stress modifiers are a variety of tactics used to lessen the negative impacts of high temperatures on the well-being and output of animals. Animals can escape direct sunshine by being given shade and cover, and they can avoid dehydration by having access to clean, cold water (33, 143). An environment can be made more comfortable by using ventilation systems and airflow control to disperse heat and humidity, as well as cooling equipment such as fans and misters (144). Resilience to high temperatures is further increased by behavioral management techniques and genetic selection for heat tolerance features. During times of heat stress, nutritional modifications are essential, such as changing the content of the feed or increasing the amount of electrolyte supplementation (34, 145). Betaine is an amino acid derivative with advantageous biological characteristics that support its use as a useful supplement during heat exposure (146).

Betaine is one example of an additive that has been shown to be effective in decreasing metabolic heat, improving heat dissipation, and increasing nutrient use in order to mitigate heat stress. It functions as a methyl donor, a chemical prebiotic involved in the methyl transfer reaction in cells, and a micronutrient for microbial cells that increases uptake during osmotic stress (146). Moeckel et al. (147) and DiGiacomo et al. (148) reported betaine's potential to mitigate heat stress by decreasing energy used and therefore metabolic heat production, while also acting to maintain osmotic balance during thermal challenge. Additionally, it stabilizes the intracellular protein structure by increasing hydrogen bonding between aqueous proteins in the folded state, acting similarly to molecular chaperones (149). When oxidative stress is present, betaine has been demonstrated to decrease the mRNA expression of HSP70 (150). However, utilizing an animal model (151), showed that goats supplemented with betaine and exposed to extended heat stress (42°C, 36 ± 2% RH, 6 h per day, for 16 days) generated noticeably lower amounts of HSP60, HSP70, and HSP90 than goats not supplemented with betaine (151). Additionally, through changes in blood chemistry and cellular metabolism, betaine supplementation may help manage heat stress indirectly. The findings of Hall et al. (152) revealed that there was an improvement in the thermotolerance of cattle-fed betaine during the thermal challenge.

The body typically shows a taurine shortage when under stress (153). For this reason, adding taurine to the diet is crucial. Taurine has positive effects on reducing stress, which may lower the amount of reactive oxygen species and shield mitochondria from oxidative damage (153). As an animal's cell-mediated immune response weakens in summer, glutamine strengthens it (154). Additionally, glutamine promotes the development of intestinal mucosa, shielding the intestine from harm under a variety of stressful circumstances (155). Broilers subjected to cyclic heat stress showed enhanced immunological response and performance attributes when supplemented with 100 mg/kg GABA (156).

7.3 Biotic agents

By producing different metabolites to activate the neurological, endocrine, and immunological systems of hosts, the gut microbiota plays a crucial role in maintaining host health (157). By suppressing pathogens, releasing immunomodulatory and bioactive factors and encouraging the growth of beneficial bacteria, probiotics can restore the ecological stability of the gut microbiota. This can also improve the function of the hypothalamic–pituitary–adrenal axis, one of the main stress response systems, and immunity through the

TABLE 5 Climate-smart feed additives and supplements.

Additive/supplement	Climate-smart attributes	Bioactive compounds	Limitations	References
Phototrophic algae	Sustainable protein source, rich in antioxidants (carotenoids, polyphenols) that neutralize reactive oxygen species (ROS) and mitigate oxidative damage. Enhances livestock thermal resilience and reduces environmental impact	Carotenoids, polyphenols, EPA, DHA	High production costs: scaling challenges for large-scale livestock use	(124–126)
Yeast derivatives	Source of antioxidants, beta-glucans, and ergosterol, supports immune function, reduces oxidative cell damage, and contributes to better stress resilience	Beta-glucans, ergosterol, antioxidants	Strain-specific responses; variable bioavailability	(128, 129)
Probiotics	Modulate gut microbiota, improve digestion and immunity, enhance stress resistance and nutrient use	Lactic acid bacteria, Pediococcus, Bacillus	Strain-specific efficacy, affected by storage and environmental factors	(158, 159)
Prebiotics	Promote beneficial gut microbes, enhance gut integrity, improve nutrient absorption	Galactooligosaccharides (GOS), Mannanoligosaccharides	Limited by diet composition and environmental factors	(161, 164)
Exogenous enzymes	Improve nutrient digestibility and absorption, reduce environmental nitrogen and phosphorus excretion	Phytase, xylanase, cellulase	Sensitive to storage and pH variations; requires careful formulation	(241)
Organic acids	Enhance gut health, reduce harmful bacteria, improve feed efficiency	Propionate, acetate, lactate	Reduced efficacy with improper application or dosage	(193)
Phytogenic extracts	Antioxidant, anti-inflammatory, methane suppression, heat stress reduction	Flavonoids, polyphenols, tannins	Effectiveness depends on plant source and dose	(200, 204)
Postbiotics	Enhance gut barrier, modulate immune response, reduce stress effects	SCFAs, polyamines, bacteriocins	Emerging research: effects not fully understood	(181, 185, 242)
Electrolytes	Maintain water and electrolyte balance during heat stress, reduce impact of climate extremes	Sodium, potassium, chloride ions	High inclusion rates can disrupt acid–base balance	(243)

microbiota-gut-brain axis or the microbiota-gut-immune axis (158). The use of probiotics, prebiotics, and synbiotics to modify the gut microbiota has emerged as a promising biotherapy approach for the prevention and treatment of a wide range of illnesses, including stress-related conditions (159).

7.4 Prebiotics

The gut microbiota is crucial for energy control and the stress response (160). Prebiotics are substances that the host cannot digest, but can be used to ferment and aid in the reproduction and metabolism of intestinal probiotics for the benefit of the host's health (161). Research has demonstrated that adding dietary GOS supplements to broiler chickens' jejunum can reduce the disturbance of intestinal integrity by averting changes in TJs and AJs (162). Furthermore, by upregulating occluding mRNA and protein expression, GOS increase intestinal bifidobacteria in rats and is important in preventing disturbance of intestinal integrity (163). Fructooligosaccharide dietary supplements also reduce *E. coli* and *C. perfringens* while increasing the diversity of Lactobacillus in chickens' gut. Mannanoligosaccharides inhibit the attachment or colonization of harmful bacteria by preventing their binding to mannan receptors on the mucosal surface, most notably *Salmonella typhimurium* (164). Additionally, mannan-oligosaccharides improve intestinal integrity by raising villus height, goblet cell count, lactobacilli and bifidobacteria populations, and lowering the amount of *E. coli* in chicken ceca (165). In Caco-2 and HT-29 cells, HMO treated with *B. longum infantis* enhanced IL-10 expression and transcription of ZO-1, occludin, and junctional adhesion molecule (JAM)-A mRNA (166). *In vivo* studies on hens exposed to heat stress revealed that adding mannan-oligosaccharides and cello-oligosaccharides (COS) to the diet helped to lessen the effects of heat on intestinal morphology and intestinal barrier function (167). By reducing HS-induced increases in pro-inflammatory cytokines and decreases in intraepithelial lymphocytes, IgA-secreting plasma cells, and mucin formation, the probiotic *B. licheniformis* promotes the GIT mucosal immunity in broilers subjected to thermal challenge (168). By boosting mRNA expression, an IgA secretion of the anti-inflammatory cytokine IL-10, *B. subtilis* B10 promotes the development of mucosal immunity in broiler chickens (169). During a 42-day heat stress phase, oral supplementation of *L. acidophilus* and *S. cerevisiae* probiotics with and without selenium supplementation reduced markers of oxidative stress and hepatic inflammation in rats (170).

7.5 Probiotics

Probiotics have been described as "live microorganisms that are beneficial to the health of the host at an adequate intake dose" (171). Probiotics have the ability to modify the composition of intestinal microbes and prevent harmful bacteria from colonizing the intestines. They have been shown to have the capacity to aid in the development of a robust intestinal mucosa protective layer, hence boosting immunity and strengthening the intestinal barrier (172).

Lactic acid bacteria (LAB), such as *Lactobacillus bulgaricus*, *Lactobacillus acidophilus*, *Lactobacillus lactis, Lactobacillus salivarius, Lactobacillus plantarum, Streptococcus thermophilus, Enterococcus faecium, E. faecalis*, and *Bifidobacterium* sp., are the bacterial species now utilized in probiotics (173). Probiotics can also include yeast (*Saccharomyces cerevisiae*) and fungus (*Aspergillus oryzae*) (173). Multiple mechanisms are involved in their action, including neutralizing enterotoxins, promoting gut integrity and maturation, improving growth, preventing inflammation, and modulating the immune system, metabolism, and oxidative stability in fresh meat (174). Probiotics have been shown to enhance gut microbial diversity. To be more precise, *Pediococcus pentosaceus* had a greater average SCFA level and *Bacillus sp.* increased body weight (175).

Heat tolerance is causally correlated with the microbial community, which includes the microbiota's population, composition, and function (176). Heat-stressed mice showed reduced levels of several probiotics, including *L. murinus* and segmented filamentous bacteria (177). It was reported that Bacteroides were greatly decreased, and Akkermansia was dramatically increased in mice when fecal microbiota from heat-stressed pigs was transplanted (178). These findings suggested that a therapeutically beneficial microbiota may have been added to the heat-stressed animals. Probiotics, prebiotics, and synbiotics have been utilized to prevent or lessen the deleterious effects of stress on physiological equilibrium (179). Under hot temperatures, the gut microbiota can be modulated by probiotic or postbiotic supplementation. Supplementing with probiotics (Bospro, Lacto-Sacc) improved physiological state, particularly thermoregulation, in the summertime (23 to 34°C, relative humidity 65 to 89%) (180). Dietary supplementation with *Bacillus subtilis* reduced heat-induced inflammatory reactions via controlling immunity (78).

7.6 Postbiotics

Postbiotics are soluble metabolic products or byproducts secreted by living bacteria or released following bacterial lysis. They are widely used because they contain a variety of signaling molecules that may have antioxidant, immunomodulatory, and anti-inflammatory properties (181). Such as probiotics and prebiotics, postbiotics work in a number of ways to have positive benefits. By preventing the growth of harmful bacteria and promoting the growth of good bacteria, they can alter the makeup of the gut microbiota, improve the operation of the gut barrier, have anti-inflammatory and antioxidant qualities, and influence the immune system (182). Various constituents are present in them, including vitamins, bacteriocins, functional proteins, peptides, SCFAs, polyamines, inactivated microbial cells, and other bioactive metabolites (181).

The addition of 0.3% postbiotics, which are made by *Lactobacillus lantarum*, improves the gut microbiota by increasing the populations of Lactobacillus and caecum total bacteria and decreasing those of Enterobacteriaceae, Salmonella and *Escherichia coli* (183). It has been shown that epithelial colorectal adenocarcinoma cells were partially protected against heat-induced damage to their monolayer integrity by pretreatment with galacto-oligosaccharides prior to heat stress exposure (40 to 42°C) for 24 h (184). Furthermore, by increasing gut-beneficial bacteria, primarily butyrate-producing bacteria, oral therapy with fermented *Saccharomyces cerevisiae* prebiotic for fourteen days prior to heat stress exposure mitigates the negative effects of heat stress (185). The postbiotic *Aspergillus oryzae* enhanced energy-use efficiency, water absorption, and intestinal permeability (186).

7.7 Other biogenic additives

The GIT taxa distribution is significantly altered by early insults to the microbiota, which have detrimental effects on the host due to the disruption of stable, selective forces that preserve a homeostatic equilibrium (187). With overlapping metabolic capacities, the reticulo-rumen and hindgut contain enormous species-and strain-level variety (188, 189). The ecological characteristics of the microbiota are critical to the stability of the reticulo-rumen and hindgut ecosystems (188).

The functionality and capacity of gut microbiota to use various substrate groups varies (190). Therefore, greater diversity and richness of these microbiota promote stability and allow for more effective utilization of food resources, making them generally advantageous (191). Therefore, the gut microbiota may be changed into a less desirable and functional condition due to the losses in richness and diversity that occur after a high-grain diet and SARA (189).

Organic acids from animal and plant tissues have been incorporated into livestock feed to improve their performance. It contains propionate, acetate, lactate, butyrate, fumaric, tannic, and caprylic acids. These acids are advantageous to birds' gastrointestinal health and functionality (192). To improve immunity, nutritional digestibility, growth performance, and avoidance of GIT disorders in broiler chickens, organic acids have been added to feeds or water (193).

7.8 Phytogenic plant extracts and essential oils

There are different compounds derived from plants that possess thermally beneficial functional compounds including antioxidant and anti-inflammatory properties that help maintain livestock well-being when facing heat stress. In recent times, there has been an increasing curiosity about the application of phytogenic feed additives (PFA) (71, 194–199). Plant polyphenols, which comprise phenolic acids, flavonoids, 1,2-stilbene compounds, and lignins, are polyhydroxy chemicals that are mostly present in plants' roots, bark, and leaves (200). Plant flavonoids are naturally occurring antioxidants that enhance cellular viability by releasing hydrogen ions and scavenging oxygen-free radicals by their binding to reactive oxygen species (201).

Plant polyphenols can boost endogenous antioxidants, including SOD, CAT, and GSH, in addition to decreasing ROS (202, 203). Plant extracts, including flavonoids and polyphenols, are commonly utilized in cattle to improve product quality, boost immunity, reduce heat stress, and increase feed intake (200). Proanthocyanidins, a polyphenol found in bearberries and green tea, can donate electrons or hydrogen atoms and act as an antioxidant (204). Medicinal plants can improve the pathways leading to mitochondrial activity (205), which can reduce the synthesis of oxidative stress and boost synthesis and supply more energy resources (206). Plant extracts primarily use four mechanisms of action to regulate oxidative stress. First, plant extracts' antioxidant components can limit pro-oxidative activity by giving metals hydrogen atoms (207). It is well known that phenols are potent antioxidants, with some researchers even arguing that their effectiveness surpasses that of vitamins E and C (208). Second, because plant extracts such as flavonoids have more hydroxyl groups in their skeletons, they may be able to deliver more electrons, which could increase their antioxidant ability (209). Third, by lowering oxygen concentrations and quenching oxygen, plant extracts can increase the antioxidant capacity in animal tissues. This prevents the generation of peroxide while activating antioxidant enzymes (210).

Additional mechanisms of action have been investigated to address the antioxidant capacity of plant extracts. These mechanisms include the modification of key proteins' expression and activity, interactions with particular proteins essential to intracellular signaling cascades, effects on epigenetic mechanisms, and alteration of the gut microbiota (211, 212).

The addition of plant polyphenol extracts from fenugreek, capsicum and green tea enhanced the intake of dry matter, milk, and milk with 4% fat-corrected milk; it also decreased vaginal temperature, enhanced welfare indices, and enhanced the AT with proteins from the acute phase response and Nrf2-oxidative stress response in dairy cows under heat stress (213). Phenolic PFAs appears to improve performance in primiparous sows and lessen oxidative damage brought on by heat stress (214). Plant flavones, which originate from the phenylpropane metabolic pathway and are secondary metabolites of plants, have been shown to alleviate hypertrophic symptoms in dairy cows (215). Because quercetin has hydroxyl groups and a B-ring twisting angle, it is a flavonoid with a high capacity for antioxidants (216).

7.9 Exogenous enzymes

Proteases, phytases and non-starch polysaccharide degrading enzyme (NSPases) improve digestion, to enhance nutrient utilization in livestock exposed to heat stress. Animal diets frequently include supplementation of enzymes, and the physiological effects of these substances are well established. In order to improve nutrient digestion and support livestock growth, feed enzymes have been incorporated into diets on a large scale. It has been shown that the best way for the livestock industry to lower phosphate excretion in animal waste is to incorporate microbial phytase into animal feeds. Additionally, it increases the amino acids availability (217). It has been demonstrated that adding proteases, phytase, and xylanase to the diets of broiler chickens and pigs increases their nutritional value by enhancing nutrient digestibility and growth (217). Furthermore, by lowering the oxidative stress response and possibly affecting the makeup of the mucosal microbiota in the small intestine, these enzymes have shown a functional advantage (217). Research is currently ongoing to determine the exact processes underlying their activities.

Catalysts such as protease, xylanase, and phytase aid in the digestion of proteins, β-1,4-xylan linkages, and phytic acid. They may also have benefits for the digestive health and microbiota of chickens and pigs (217). Based on their intended use, commercial enzymes fall into three primary categories: Phytase breaks down fiber into smaller components by targeting phytate molecules, which are generated from phosphorus (218). Cellulases and beta-glucanases, on the other hand, target cellulose polysaccharides and NSPs, respectively. Proteases, on the other hand, work on proteins to improve digestion. In conclusion, alpha-amylase enzymes function as starch and enhance nutrient digestion (219). Depending on specific needs, an animal's diet may contain a single enzyme or an enzyme cocktail (220). For example, regular digestive tract enzymes can also be used in conjunction with the traditional use of xylanase, glucanase, phytase, and, more recently, multi-carbohydrase preparations (217).

In addition to advantages in the lipid and oxidative profile of meat, a blend of exogenous enzymes (amylase, protease, cellulase, xylanase, and beta glucanase) in the individual and combination form in the feedlot steers diet positively altered nutritional indicators (221). Dairy cows and beef cattle operate more productively when given exogenous fibrolytic enzymes; nevertheless, the right combination of cellulases and xylanases relies on the content of the feed in ruminant diets (222). It is believed that feeding yeast cultures (YC; *Saccharomyces cerevisiae*) and fibrolytic enzymes (cellulases and hemicellulases) made by bacteria and fungi will improve fiber digestion, raise post rumen nutrient flow, and stabilize rumen pH (223). This could be beneficial to cows during heat stress. When xylanase is added to a diet of wheat co-products from flour milling that include high levels of arabinoxylan and NSP, it has been shown to increase energy digestibility in pigs (224). Studies on adding xylanase to broiler chicks have continuously shown benefits, including decreased digesta viscosity and increased nutritional digestibility (225). Energy use has been reported to be enhanced by the phytase enzymes obtained from *Aspergillus niger*, *Peniophoralycii*, *Schizosaccharomyces pombe*, and *Escherichia coli* (226).

8 On-farm feed production

By utilizing the socioeconomic and agro-ecological conditions of the region, semi-arid Southern Africa offers exceptional prospects for the domestic production of climate-smart animal feeds. Among the main feed sources are:

- Crop residues: There are abundant drought-tolerant crop residues in the area, including sorghum, millet, and cowpea, which can be turned into inexpensive animal feed. Their nutritional value can be increased by processing techniques as chopping, urea treatment, or ensiling.
- Forage crops: Because of their high feed quality and resistance to drought, species such as *Leucaena leucocephala*, Stylosanthes spp., and *Cenchrus ciliaris* (buffel grass) are suited for cultivation.
- Agro-industrial by-products: These excellent feed materials, which are in line with the circular economy principles, include brewer's spent grains, sunflower meal, cottonseed cake, molasses, among other by-products from nearby agricultural sectors.

- Insects and algae: Because of their low resource requirements and capacity to adapt to local conditions, emerging feed sources such as spirulina and larvae of Black Soldier Flies hold promise for scaled production.

The capacity for various farming systems to incorporate different feed interventions varies:

- Smallholder mixed crop-livestock systems: Utilizing crop wastes and forage crops can help these systems, which are prevalent in semi-arid areas. Simple technologies such as hay baling and silage-making can be used by small-scale farmers to preserve food for dry seasons.
- Commercial livestock operations: To increase feed efficiency and lower input costs, larger-scale commercial systems can use hydroponic fodder systems, high-protein concentrates, or processed by-products.
- Pastoral systems: To reduce overgrazing and soil damage, pastoralists in arid regions can use energy-rich feed blocks or supplements to keep livestock alive during times when grass is sparse.
- Agro-pastoral systems: By combining crops that may be used for both food and feed (such as sorghum and maize), these systems can optimize resources.

9 Animal genetics and climate-smart livestock nutrition

Climate change threatens livestock productivity through heat extremes which overwhelm artificial climate controls and disrupt animal homeostasis. Heat stress alters the expression of genes which are involved in the control of metabolism and immune responses, which may compromise animal performance (227). As heatwaves increase and intensify, the genetic gains achieved in livestock are therefore at risk. Epigenetics, nutrigenomics and nutrigenetics present different solutions which target the genes for stress tolerance and productivity.

Epigenetics describes heritable changes in gene expression which occur without altering the DNA sequence, which are triggered by environmental factors such as temperature and nutrition. It involves molecular modifications such as DNA methylation and histone protein changes which alter how genes are expressed (68). By identifying specific epigenetic markers, breeders can select animals which are most equipped to cope with heat stress (228). Nutritional epigenomics targets these epigenetic mechanisms through the diet. For example, choline, folate, and betaine can act as methyl donors in epigenetic medications which alter gene expression to mitigate the effects of heat stress (228, 229).

Nutrigenomics is about how dietary nutrients influence the expression of genes which control stress tolerance, metabolism, and productivity. For example, antioxidants and amino acids such as methionine are known to regulate genes involved in stress resistance and metabolic efficiency (230). Additionally, dietary components such as selenium and omega-3 fatty acids have been shown to boost the expression of heat shock proteins and antioxidant enzymes. By targeting specific metabolic pathways, nutrigenomics can be used to enhance thermal tolerance while maintaining productivity and feed efficiency (78).

10 Policy interventions

Investments in infrastructure for feed processing and storage, such as silos and pelletisers, are crucial for a successful integration. Climate-smart feed solutions should be adopted by farmer cooperatives and local production should be encouraged by policy initiatives. In order to increase the ability of smallholder farmers and pastoralists, extension services are essential.

A supportive policy is therefore crucial for the success of CSLN. Climate-smart policies should be sensitive to the large variability in the availability and use of land resources between regions, countries and land management systems and in socio-economic conditions, such as wealth, degree of industrialization, institutions and governance, which affect the capacity to respond to climate change (231). Being integral to broader CSA interventions, CSLN may benefit from climate responses such as crop diversification, yield and nutrient improvements, planted area expansion and intensification, which, in risking GHG emissions, conflict with climate change mitigation (232). Therefore, a complex, livestock nutrition focused, land-energy-water-food-livestock-environment nexus approach remains critical to managing the peculiar synergies and trade-offs associated with CSLN interventions (Table 6).

TABLE 6 A policy framework to support climate-smart livestock nutrition practices.

Policy	Action	Deliverables	References
Financial incentives	Provide insurance and financial support to farmers adopting climate-smart feeding practices.	Adoption of climate-smart feeding practices	(1, 10)
Research funding	Invest in research and development for climate-smart feeding technologies.	Innovations and continuous improvement in CSLN	(7, 8)
Regulations on GHG emissions	Develop and implement guidelines and rules to reduce GHG emissions from livestock production systems.	Climate-smart livestock practices to meet legal emission targets.	(1, 232)
Awareness campaigns	Conduct educational programs to inform farmers about the benefits of adopting climate-smart livestock nutrition.	Knowledge and wide-scale behavior change.	(10, 13)
Market incentives	Establish premium markets for sustainably produced livestock products.	Develop climate-smart value chains and economic benefits derived from adopting sustainable practices.	(10, 25)

11 Conclusion and recommendations

Southern Africa's livestock production systems are increasingly challenged by adverse climate change which exacerbates feed scarcity, reduces feed quality, and exposes livestock to thermal stress. The concept of CSLN is a potential solution, whose objectives include adapting to declining feed availability, enhancing livestock resilience to heat stress, and minimizing the environmental footprint of livestock production. The concept of CSLN advocates for alternative, climate-resilient feed sources. To enhance livestock resilience to heat stress, CSLN emphasizes dietary strategies that incorporate natural antioxidants, electrolytes, and polyphenols, which reduce oxidative stress and improve thermoregulation in animals, minimizing the need for synthetic additives, which are an option. For environmental sustainability, precision feeding and the use of circular feed systems are recommended to reduce greenhouse gas emissions and optimize the use of land, water, and energy resources.

Sustainability and feed-food competition must be carefully considered when adopting climate-smart alternative feedstuffs. A workable alternative is provided by dual-purpose crops and tree shrubs, which act as ecological enhancers and feed resources. Their incorporation into agricultural systems could guarantee feed availability while reducing land degradation and deforestation. To improve their production and use at scale, further research is necessary, backed by investments and regulations that serve larger objectives for environmental preservation and food security.

Analyses of the scope for CSLN supported the following key recommendations for its success;

- Developing climate-resilient feed systems: Investment in research and development of a broad range of alternative, sustainable feed sources that are locally adapted to Southern Africa's semi-arid conditions is critical. This includes insect meal, climate resilient, cultivated and wild forage and food crops, agro and other by-product feedtuffs.
- Improving livestock resilience to thermal stress: Feed formulations which utilize different biotics and phytogenic additives and incorporate synthetic bioactive compounds such as antioxidants and electrolytes that enhance the animals' ability to cope with heat stress. These strategies should be complemented by selective feed plant and animal breeding for heat tolerance.
- Promoting environmental sustainability: Policies which encourage circular feed systems that reduce resource wastage, lower GHG emissions, and make efficient use of land, water and energy resources through agro-ecological practices.
- Policy and financial incentives: Governments and development organizations to provide financial incentives and insurance schemes to encourage farmers to adopt climate-smart feeding practices and promote the development of climate-smart feed and animal product supply chains.
- Research funding: Research directed toward climate-smart technologies to ensure continuous improvement.

Author contributions

FF: Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing, Conceptualization. TC: Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing, Conceptualization. OO: Conceptualization, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing.

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From tradition to precision: leveraging digital tools to improve cattle health and welfare

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Traditional cattle production practices relied heavily on manual observation and empirical decision-making, often leading to inconsistent outcomes. In contrast, modern approaches leverage technology to achieve greater precision and efficiency. Advancement in technology has shifted to a new dimension of predictive and monitoring in cattle health management. This review aims at highlighting the available and current digital technologies in cattle health, evaluate their utility in practice, and identify possible future advancements in the field that can potentially bring even more changes to this industry. The paper highlights some of the barriers and disadvantages of using these technologies, such as data security issues, high capital investments, and skills gap. The integration of these advanced technologies is set to play a fundamental role in enabling the livestock industry to meet the rising global demand for high-quality, sustainably produced products. These technologies are essential for ensuring compliance with ethical standards and best practices in cattle care and well-being. In light of these advancements, the application of digital innovations will support the achievement of socially responsible cattle production, while simultaneously maintaining optimal levels of animal health and welfare.

KEYWORDS
digital revolution, cattle health, welfare, precision livestock farming, internet of things, artificial intelligence, predictive technologies, monitoring systems

1 Introduction to digital tools in cattle health

A key goal of livestock rearing is to ensure optimal health and welfare of animals, not only for ethical and economic reasons, but also to meet increasing societal demands for products that are originated from animals with high welfare standards, i.e., raised under conditions where they can thrive (1, 2). Digital technologies that quantify aspects of animal behavior, physiology, and production over time have the potential to contribute to the identification of welfare and health related problems early on (3).

This in turn can enable a rapid intervention at herd or individual level to improve the animals' living conditions, prevent animals from suffering, improve treatment efficacy and reduce antibiotic consumption (4, 5). This mini-review provides an overview of the most common digital tools currently used within the cattle sector where the integration digital tools has led to enhanced monitoring capabilities, allowing farmers to collect real-time data on cattle health and behaviors. By utilizing technologies such as wearable sensors, drones, and mobile applications, stakeholders can make informed decisions that promote better welfare outcomes and disease prevention strategies. Digital tools have led to practical improvements for both researchers, the cattle industry, and veterinarians.

The use and market penetration of digital technologies for health management within the cattle sector is considered relatively low in some countries when compared to other sectors such as pig or poultry farms. Initially, digital tools in the cattle sector were mainly introduced as an aid to both monitoring production quantities and quality. Indeed, the need to support management decisions on a range of aspects such as feeding, heat detection, the timing of insemination, and the knowledge around the different growth curves created a demand for data collection tools (3, 6) (Figure 1).

At a herd level, management tools now allow for automated data collection and herd management, outfitted with data collection on production details, such as yields and compositions, for all cows. In certain nations, the implementation of data management tools differs depending on the respective industry sector (7). For example, France and Ireland demonstrate significantly contrasting proportions of dairy farms employing cow identification, monitoring milk production peaks, and engaging with a milk advisor. Recent studies have also documented that specific digital tools have facilitated optimization of labor productivity, logistics, and operations, or have improved the monitoring of technical data (8, 9).

2 Practical applications of digital technologies in cattle management—case studies

Animal-friendly cattle management strategies, which include providing the best possible conditions for the health, welfare, and productivity of cattle, are key factors in achieving sustainability in cattle production systems (10, 11). In this context, the use of digital technology in the field of cattle management can facilitate more effective and efficient preventive as well as curative animal care. These applications encompass both on-animal devices and sensors embedded within the living environment, which monitor the behavior, breeding, and health of cattle (12, 13).

Traditionally, the animals' behavior and health are controlled by visual observation and handling, and are frequently influenced by treatment. As the livestock sector is evolving, the farmers' opportunities to work with the herd and the animal caretaker's activity periods must also be considered (14). Given the forecasted shortage of 64,000 workers by 2028 that the dairy sector alone faces, as well as the urgent need to focus on both improving farm efficiency and increasing animal health and welfare, there is an ongoing need to develop technologies that are science-based for ensuring minimal disturbance of the animals, as well as a better and more efficient use of resources. Similarly, concerns about the safety and quality of dairy products have led to development for innovative methods and tools of assessment (15, 16).

Recent advancements in AI, IoT, and sensor technologies have improved cattle health monitoring, disease prevention, and farm management. Their impact is demonstrated through several case studies carried out over the past years. One such study was conducted by Marku et al. (17) who explored the implications of digitalization in livestock farming in two distinct settings: Baden-Württemberg (Germany), respectively North Savonia (Finland). Farmers in Finland, for example, perceive digitalization as an

FIGURE 1
From tradition to precision in cattle farming.

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essential catalyst in boosting collaboration with industry partners, facilitating access to new markets, and optimizing financial resource allocation. In contrast, German farmers were less confident of its transformative impact on these elements, emphasizing regional differences in digital usage. These findings highlight the importance of personalized digital approaches that address farm-specific and regional difficulties in order to fully reap the benefits of precision livestock production.

Digi4Live, a Horizon Europe project spanning 2024–2028, exemplifies the multinational efforts to advance digital livestock technologies (18). The initiative, which includes 16 partners from nine countries, intends to boost digital technology adoption in the European cattle sector, benefiting farmers, agribusinesses, and policymakers. The effort aims to create over 50 data-driven cattle management solutions using embedded sensors, AI-powered computer vision, and IoT technologies. Digi4Live has pioneered two key technologies for cattle monitoring. The first one is Computer Vision for Behavior Analysis, a technology that automates behavior tracking, enhancing animal welfare assessment. GPS Sensors for Dairy Cows, is the second solution developed, designed to monitor outdoor access and grazing patterns, thus improving sustainability and resource efficiency. To strengthen AI-based animal tracking, the project integrates multi-farm datasets from 20 dairy farms with diverse environmental conditions. A novel web-based tool, called Smart Labeling Loop, that facilitates manual data labeling to train neural networks, ensuring robust algorithm development will also be developed. The project's goal is to demonstrate the reliability of digital tracking technologies across different farm settings, refine prediction models for outdoor access, and establish general guidelines for AI-driven monitoring systems (18).

Beyond improving livestock monitoring, Precision Livestock Farming (PLF) technologies are also recognized as an effective strategy for greenhouse gas (GHG) mitigation. In a study conducted by (49), data from the Scottish Cattle Tracing System (CTS) was used to model the impact of PLF adoption on carbon emissions in beef production systems. The research team developed two baseline scenarios—one for grazing systems and one for housed systems—and calculated emissions using the Agrecalc carbon footprinting tool. They analyzed the effects of automatic weigh platforms, accelerometer-based estrus detection sensors (fertility sensors), and health sensors for early disease detection on farm-level emissions. The findings indicated that PLF adoption had a greater impact in housed systems than in grazing systems, suggesting that technology-driven efficiency improvements could significantly reduce the carbon footprint of beef production. Although this study focused on Scotland, it is likely that similar emission reductions can be achieved in other European countries with comparable farming practices.

The use of PLF sensors represents an essential mechanism to reduce how climate change affects dairy cattle welfare. The research by Ranzato et al. (19) evaluated behavioral adaptations of Italian Holstein cows under heat stress conditions on a precision livestock farming facility. The dairy farm experienced three hot weather events defined as heat waves that lasted for five straight days where the temperature-humidity index exceeded 72 in the summer of 2021. A study with 102 cows studied milk yield records to identify animals that showed reduction in milk without concurrent mastitis symptoms. The ear-tag-based accelerometer sensors tracked both the time spent laying down and chewing action alongside total movement patterns. Results from the research revealed heat waves prompt all cows to chew more often and move around more frequently during the day while shortening the time they spend resting. Heat-sensitive animals spent 15 more daily minutes carrying out these activities. Device-generated frequent sensor data enables accurate identification of cows requiring specific heat stress relief methods resulting in better animal welfare outcomes along with production gains.

3 Future developments and innovations in digital tools for cattle health

The constant improvement of technological innovation in recent decades is providing a solid and competitive base for the "fourth agricultural revolution," a "digitally augmented era" which is expected in the coming years (9). In animal production, different digital technologies, in particular the Internet of Things, big data, robotics, and artificial intelligence, provide the basis to originate the so called Precision Livestock Farming (Table 1). This allows for the continuous collection of an ever-increasing amount of data of direct interest, which may be sent and processed so that new decisions may be made in a positive feedback loop (20).

The expanded capabilities of sensors and data processing, together with advances associated with cloud computing, fast analytical algorithms, big data, and machine learning, are enabling ambitious and complex systems to be developed not only for highly specialized applications in different contexts like smart farming agriculture-oriented, but also for the smart livestock tasks (21). When it comes to cattle, possibly the best-known application of Internet of Things tools is the automatic milking system (22). Technologies for milk production monitoring include, in addition to equipment for milking, radiofrequency identification ear tags and collars, as well as accelerometer-based devices that monitor the activity and rumination of individual animals (23, 24).

These tools are either utilized as separate devices on individual animals or combined together to complement the data in the "Integrated System" of production, in a farming automation context, very close to the Internet of Living Things vision. Over the past years, various IoT tools that provide risk alerts to improve on-farm control of animal welfare, allowing for the early detection of diseases like respiratory infections, nutritional alterations, mastitis or physiological modifications such as calving, or estrus have been developed (25).

4 Challenges and barriers to implementing digital technologies in cattle production

In order to effectively deploy digital technologies across a broad spectrum of cattle producers and related industries like those related to health and welfare, it is important to appreciate and address barriers to scaling that deployment. This is specifically important, as animal welfare is ultimately the responsibility of the owner and the manager of the animal, regardless of the level of digital assistance (26). There

TABLE 1 Applications of digital technologies in cattle management.

Domain of application	Research developments	Benefits	Challenges	References
Health, reproduction, feeding and behavior monitoring	Wearable devices track health and feeding data—e.g., movement activity, feed intake, frequency, duration—in real-time using IoT-enabled sensors. Technologies such as bioacoustics, accelerometers, infrared thermography are also employed for collection of data. Using artificial intelligence, deep learning, cloud-based systems analyze data to identify anomalies and provide farmers practical insights. Predictive analytics research is being conducted to foresee changes in feeding habit caused by health or environmental conditions.	Early detection of diseases or stress through real-time monitoring, reducing mortality rates and improving animal welfare. Optimized feeding strategies based on individual animal needs, enhancing growth efficiency and reducing feed waste. Behavioral insights help identify issues like lameness or aggression, enabling timely interventions.	High initial costs for sensors, cameras, and data management systems. Data overload can overwhelm farmers without proper training or analytical tools. Wearable devices may cause discomfort or require frequent maintenance.	(19, 30–34)
Non-invasive weight assessment	Automated systems use imaging technologies, load cells, or 3D cameras to estimate animal weight without physical handling. This reduces stress on animals and provides continuous growth data, helping farmers adjust feeding regimes and predict market readiness.	Non-invasive weight measurement reduces stress on animals and labor for farmers. Continuous growth tracking allows for precise feeding adjustments and better market timing. Improves breeding and selection processes by providing accurate performance data.	Accuracy can be affected by animal movement or environmental factors. High upfront costs for imaging systems or load cells. Requires calibration and technical expertise to ensure reliable data.	(35–37)
Environmental monitoring	IoT-enabled sensors to monitor environmental parameters such as temperature, humidity, air quality, and ammonia levels. Automated ventilation, misting and heating systems can be adjusted based on real-time data.	Ensures optimal living conditions, improving animal health and productivity, especially in the context of heat stress Reduces energy costs by automating ventilation, heating, and cooling systems. Minimizes environmental impact by controlling emissions like ammonia and methane.	Sensors and IoT devices require regular maintenance and calibration. Data integration from multiple sensors can be complex. Initial setup costs may be prohibitive for small-scale farmers	(38–40)
Traceability of the dairy and beef supply chain	RFID and GPS technologies are widely adopted for tracking livestock movement across the supply chain. AI-powered analytics predict bottlenecks and optimize logistics, ensuring timely delivery and animal welfare. Research focuses on blockchain integration for enhanced traceability and transparency. AI models are being developed to predict supply chain disruptions and optimize inventory management.	Enhances food safety by enabling quick identification of contamination sources. Builds consumer trust through transparency in product origins and handling. Improves supply chain efficiency by reducing losses and streamlining logistics.	Implementing blockchain or RFID systems requires significant investment. Data privacy and security concerns may arise. Small-scale producers may struggle to adopt these technologies due to cost and complexity.	(41–44)
Market dynamic analysis	AI analyzes market trends, demand–supply dynamics, and price fluctuations, providing predictive insights for production and exports. IoT sensors collect data at various supply chain stages for real-time market analysis. Research is advancing in AI models for more accurate market predictions, including consumer preferences and global trade trends. Integration of AI with blockchain for secure and transparent market data sharing.	Enhances food safety by enabling quick identification of contamination sources. Builds consumer trust through transparency in product origins and handling. Improves supply chain efficiency by reducing losses and streamlining logistics.	Implementing blockchain or RFID systems requires significant investment. Data privacy and security concerns may arise. Small-scale producers may struggle to adopt these technologies due to cost and complexity.	(45–48)

are many different types of cattle production systems, but not all of these systems are applicable to every single production context. For example, high-input outdoor grass-fattened cattle operations will face very different issues and require varying resources than low-input extensively managed animals do.

Additionally, these concerns are distinct from those encountered in feedyards, where conditions and management strategies vary significantly. Each type of production has its own unique set of challenges and advantages, tailored to its specific approach in the cattle industry (27). The aim of cattle production and the associated challenges are very different in these settings. Producers are motivated by many different factors to adopt technology. Ultimately, those products that can improve efficiency or overall economics are needed. Access to cost-effective technology is also a critical limit to many adoption issues (7, 28). Products that do not pay for themselves in a reasonable amount of time may not be adopted. Since not all production practices are alike, the potential economic benefits of a digital technology may not apply to everyone, which limits the target audience.

The digital divide, that is, a gap in labor skill or access to technology, might also limit the number of users (29). Additional training or troubleshooting may be required when implementing new technologies, especially in environments where the use of technologies does not occur regularly. A perceived lack of value to the producer might also reduce willingness to invest, even if the product is now affordable. Returns and overall positive outcomes are easier to demonstrate to potential buyers if supported by data; while product manufacturers may provide data, they may also be biased. Data ownership and data rights are very important, as the data may be leveraged in both the short term and long term (28). It is also not uncommon for the potential user to have several reasons why adoption would not be beneficial to them, which is what extension and academia are trying to uncover, understand, and ameliorate.

Research is important to identify barriers, including actual technology adoptions. Qualitative data can also provide insights into motivations and actions for each specific region, since the concept of one size fits all, may not be applied to all contexts.

5 Conclusion

The future is bright, bearing in mind predictions regarding the advances in artificial intelligence over the coming years. This could take the form of more sophisticated image analysis that is able to monitor more traits of interest. Developments in sensor technology in terms of miniaturization and computing capability are also expected to assist with this. For those technologies that are currently emerging, such as the deployment of wearable sensors for calf monitoring, opportunities will need to be identified for how and where these systems are adopted.

Many of these digital technologies are underpinned by artificial intelligence or machine learning. Collectively, the application of digital technologies is seen to improve economic productivity, including through improved animal health, welfare, and environmental sustainability. A common thread throughout the subsections was the role of digital technologies not just as a tool but as a driver to deliver sustainable changes to beef and dairy farming. The uptake of digital technologies is delivering significant data and information for management analysis, environmental assessment, managing carbon emissions, feeding practices, and the delivery of new consumer-facing options. Although the adoption of digital technologies is accelerating at an unprecedented pace, many of the present findings not yet reflect the leading edge of development.

Ongoing practical application and adaptive research, aimed at policy and practice application, must be encouraged to inform regarding the development and uptake of digital technologies. These will further encourage a mutually beneficial engagement between the cattle industries, associated stakeholders, and the digital technology sector. It is evident that cattle farming practices of the future will require substantial multi-industry, cross-institutional decision-making and engagement. It is both an exciting time and opportunity for the livestock monitoring and digital technology industries. While the deepening and implementation of this knowledge and use of digital technologies will benefit the economy and social well-being, it will also benefit the global cattle industry, our ecosystems, and the outputs of associated support industries.

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Conflict of interest

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Effect of heat stress on ileal epithelial barrier integrity in broilers divergently selected for high- and low-water efficiency

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Water scarcity and rising global temperatures are two of the greatest current and future threats to poultry sustainability. Therefore, selection for water efficiency (WE) and heat resilience are of vital importance. Additionally, intestinal integrity is of critical importance under challenging conditions to maintain nutrient absorption and therefore, growth and performance of broilers. Here, we examined the effect of chronic cyclic heat stress (HS) on the ileal expression profile of tight-junction, gap-junction, adherens, and desmosome genes in the fourth generation of divergently selected low (LWE)- and high water efficient (HWE)-chicken lines. LWE birds exhibited higher levels of gut permeability, regardless of temperature, as measured by fluorescein isothiocyanate−dextran (FITC-D). Among the claudins (CLDN), *Cldn1* showed greater expression in the HWE as compared to LWE, regardless of temperature. *Cldn5*, *-16*, *-20*, and *-34* genes were all greater in LWE and lower in HWE during HS. Conversely, *Cldn25* was decreased in LWE but increased HWE under HS. *Cldn4* was increased in the HWE line and decreased by HS. Cingulin (*Cgn*) gene expression was lower in HWE as compared to LWE and lower in HS as compared to thermoneutral (TN) condition. Gap junction protein α1 (*Gja1*) and desmoglein 4 (*Dsg4*) were greater in the HWE as compared to the LWE. Cadherin 1 (*Cdh1*) gene expression was greatest in the HWE in TN conditions and lowest in HWE under HS, whereas catenin α2 (*Ctnna2*) and desmocollin 1 (*Dsc1*) were highest in HWE during HS compared to all other groups. This differential expression of key genes associated with intestinal barrier integrity likely contributes to the water efficiency phenotype and the response of these birds to HS.

KEYWORDS

broiler, heat stress, water efficiency, gut integrity, gene expression

1 Introduction

Water insecurity is a significant current concern worldwide, with the threat of scarcity only projected to rise with global warming. As of 2023, approximately half of the global population faces some form of water insecurity for at least 1 month a year, and one-fourth face extremely high levels of water stress, withdrawing over 80% of their renewable annual freshwater supply (Kuzma et al., 2023). As global temperatures are predicted to rise, and rainfall patterns shift, an ever-increasing segment of the world population will experience water stress (Greve et al., 2018). Combating this rising concern will require action at every level; however, agricultural industries must balance any changes in water usage with potential impacts on productivity. To this end, our research group has generated two lines of chickens divergently selected for water efficiency (ratio of water consumed to body weight gain). Under thermoneutral conditions, these high water efficient (HWE) birds had 3- and 47-points better feed (FCR) and water conversion ratio (WCR), respectively, compared to their low water efficient (LWE) counterparts (Aloui et al., 2024). Under chronic heat stress conditions, the HWE line drank less water and also had better FCR and WCR compared to the LWE birds (1.47 vs. 1.51 for FCR and 2.65 vs. 3.12 for WCR), indicating that they are resilient to heat stress (Aloui et al., 2024).

It has been well established that modern broilers are particularly susceptible to elevated temperatures, with decreases seen in growth, productivity, and livability (Lara and Rostagno, 2013). Virtually all dietary nutrients, including water, are absorbed across the epithelium of the intestine, and the importance of gut health and integrity has become increasingly understood across all species. Heat stress has been shown to negatively impact intestinal morphology (crypt depth, mucous area, and villus height), and leads to decreases in nutrient absorption (Marchini et al., 2011). Breakdown of intestinal integrity, known as leaky gut syndrome, also allows for increased translocation of harmful substances (bacteria, toxins, *etc.*), which is further associated with increased incidence of disease. Intestinal barrier integrity is maintained through the stability of distinct intercellular junctional complexes known as tight junctions, adherens junctions, gap junctions, and desmosomes (Vancamelbeke and Vermeire, 2017). Altered expression or changes in the structure of these complexes result in decreased nutrient absorption, as well as increased passage of ions and water to the intestinal lumen (Barmeyer et al., 2015). However, how these factors may be impacted by selection for water efficiency in poultry has yet to be determined. Therefore, here, we examine the effects of HS on ileal barrier integrity in two lines of broilers divergently selected for high and low water efficiency.

2 Materials and methods

2.1 Care and use of animals

All animal care and use were conducted in accordance with the recommendations in the guide for the care and use of laboratory animals from the National Institutes of Health. The protocol was approved by the University of Arkansas Animal Care and Use Committee (protocol # 23015). Full details of divergent selection for the LWE and HWE lines and the experimental design have been previously reported (Aloui et al., 2024). Briefly, for the genetic selection program, the base population utilized was a 2015 Modern Random Bred (MRB) population (broiler (meat-type) chickens) and the selection trait was water conversion ratio [WCR = water intake (g)/body weight gain (g)] as described previously (Aloui et al., 2024). On day of hatch, male chicks (240 chicks/line) were individually wing-banded for line identification and weighed, then placed in 12 controlled environmental chambers in the Poultry Environmental Research Laboratory at the University of Arkansas (2 floor pens/chamber, 6 chambers/line, 20 birds/pen). Each pen was covered with clean pine wood shavings and equipped with separate hanging feeders and a nipple water line attached to a low-flow water monitoring system (Hiltz et al., 2021). Water and standard diets were provided *ad libitum,* with industry standard rearing temperatures and light cycles. On d29, birds were exposed to thermoneutral (25°C) or chronic cyclic heat stress (36°C for 9 h/day from 9:00 a.m. to 6:00 p.m.) conditions (3 chambers-6 pens-120 birds/line/environment). On d49, birds (n = 12/group) were humanely euthanized by cervical dislocation and approximately 3–4 cm ileum section (~3 cm anterior to the ileocecal junction) was dissected, snap frozen in liquid nitrogen, and stored at −80°C for further analysis.

2.2 Determination of serum fluorescein isothiocyanate-dextran (FITC-D) levels

Serum FITC-D concentrations were determined as previously described (Ruff et al., 2020; Tabler et al., 2020). Briefly, 12 birds from each group were orally gavaged with FITC-D (8.32 mg/kg, MW 3–5 kDa, Sigma-Aldrich, St. Louis, MO). One hour post gavage, blood was collected from the brachial wing vein, serum separated, and fluorescence was measured (Ex 428 nm/Em 528 nm) using the Synergy HTX multi-mode micro plate reader (BioTek, Winooski, VT).

2.3 RNA isolation, reverse transcription, and quantitative real-time PCR

Total RNA extraction and RT-qPCR conditions were previously described (Aloui et al., 2024; Tabler et al., 2020; Greene et al., 2024; Dridi et al., 2022). Briefly, total RNA was extracted from the ileum using Trizol reagent (ThermoFisher Scientific, Waltham, MA) according to manufacturer's protocol. RNA concentration was determined using the Take 3 micro volume plate and Synergy HTX multi-mode microplate reader (BioTek, Winooski, VT). RNAs (1 µg) were reverse transcribed *via* qScript cDNA SuperMix (Quanta Biosciences, Gaithersburg, MD) in a 20-µL total reaction. Real-time quantitative PCR (Applied Biosystems 7,500 Real-Time PCR system) was performed using 5 µL of 10×-diluted cDNA, 0.5 µM of each forward and reverse specific primers for each gene, and SYBR Green Master Mix (ThermoFisher Scientific, Rockford, IL) in a total 20-µL reaction. Oligonucleotide primers specific for chicken were used as previously reported (Tabler et al., 2020), or as provided in Table 1. Relative expression of target genes were determined by the $2^{-\Delta\Delta CT}$ method (Schmittgen and Livak, 2008), with LWE under TN conditions used as calibrator.

2.4 Western blot

Western blot was performed as previously described (Lassiter et al., 2015). Briefly, ileal tissue was homogenized in lysis buffer containing protease- and phosphatase-inhibitors. Protein concentrations were determined *via* Bradford assay (Bio-Rad, Hercules, CA) and the Synergy HTX multimode microplate reader (BioTek,

TABLE 1 Oligonucleotide qPCR primers.

Gene[a]	Accession number[b]	Primer sequence (5′-3′)	Orientation	Product size, bp
Cldn1	NM_001013611.2	CCCACGTTTTCCCCTGAAA	For	61
		GCCAGCCTCACCAGTGTTG	Rev	
Cldn2	NM_001277622.1	CCCAGCTGATGGCAAAGG	For	61
		AGGCTGATGGCACCAAAATAGT	Rev	
Cldn4	XM_003642382.6	CGAGGTGAGATCCCCGAAA	For	71
		GGGCGTTTGGTGCTCTTCT	Rev	
Cldn5	NM_204201.2	ACGTCGTTTTGTTCCGTTGTT	For	57
		CTCAAAGGCGCACAGATCAG	Rev	
Cldn8	XM_004938379.5	CCGTGCCAAGTGTTACCAAA	For	148
		CCCTAGGTTTAAATGGGAAGATTTT	Rev	
Cldn9	XM_004946417.5	AGCATCGTCACCAACTTCTACAAC	For	64
		CAGCCCCCAGCTCTCTCTT	Rev	
Cldn10	NM_001277767.2	CCGCTGTCTGTCTGGGTTTC	For	59
		TGTGCACTTCATCCCAACCA	Rev	
Cldn11	XM_040679570.2	TTCCCCCGGTCATCAGTATG	For	62
		GTTACGTATCGCAGCGTTAGGA	Rev	
Cldn12	XM_040665727.2	GAGCCTGCCTTCTCCCTTCT	For	67
		AGAGGCATAGCTGTGCATGCT	Rev	
Cldn14	XM_015300231.4	GCGGTCTCTGGAGGGATTG	For	58
		AAACGGGTACCAGGCATGTG	Rev	
Cldn15	XM_046898719.1	TGGCAGCCTTCACCACCTA	For	63
		CGTGATTCCTTCCACTGCTTCT	Rev	
Cldn16	XM_426702.6	GCTCTGGCTTGTTGTAGGTTACAG	For	72
		TGTAGAGCATGAAATCACCTTAGCA	Rev	
Cldn19	XM_003642541.5	CACCAAGAGCCGCATTGC	For	57
		CACAGACCGCAGAGGATGAA	Rev	
Cldn20	XM_040667274.2	CTCGCAGGAATTTTTGGATTAGTAC	For	71
		TGGTCCAGAAAATTGGAAATGA	Rev	
Cldn22	XM_040699650.1	TTCGGTCCATTACGCAGTAACA	For	66
		GGCCTAGTTTCAGTTTCCAAGTG	Rev	
Cldn23	XM_004941160.5	TGGGATGTGCTGGAAGATGA	For	87
		GTCACCGTCCTGGAGCTACAG	Rev	

(Continued on the following page)

TABLE 1 (*Continued*) Oligonucleotide qPCR primers.

Gene[a]	Accession number[b]	Primer sequence (5′-3′)	Orientation	Product size, bp
Cldn25	XM_004948061.5	CCACCACTCACACCCCAAA	For	58
		CAGCCGAAATCCGCAGTCT	Rev	
Cldn34	XM_040659461.2	GTGGGTGGCTGCTTCTACGT	For	64
		AGAAGTTATGGCTCACTGGAATCAG	Rev	
Nectin1	XM_040690205.2	CCGGCAACCGGGAAA	For	65
		GCCCTCCATCCGATTCGT	Rev	
Afdn	XM_040669052.2	TCCGGAAGGACATAGAATACATTG	For	80
		AGATGTGCTAGAATCCACAGATGAAT	Rev	
Gja3	NM_001040644.2	GTGGGAAGGCCTGGGTTT	For	76
		TTGCTATTTTCCCCCACTACAAC	Rev	
Gjb1	NM_204371.3	ACAAGCAGAACGAGATCAACCA	For	69
		TGCGGCGCAGCATGT	Rev	
Gjc2	NM_001199581.2	TGGAGCCCTTAGGATGTTGTG	For	63
		GAGTCGTCGGTGCCTTGGT	Rev	
Gjd2	NM_204582.2	GCTGACCGTGGTGGTGATC	For	62
		CGTACACCGTCTCCCCTACAA	Rev	
Cgn	NM_001347391.2	CCCTCTTCTTCATGGCTTTTTG	For	131
		CCGAGGGACACAATTGCATA	Rev	
Cdh2	NM_001001615.2	GACCCTACAGCCCCACCATA	For	61
		TGGAGCCGCTTCCTTCATAG	Rev	
Ctnna2	NM_205136.2	GAATTGCCTCTTCAGAGTTTGCA	For	57
		TCGTGCCCCGCTTCAC	Rev	
Ctnnb1	NM_205081.3	TGCCCCACTGCGTGAAC	For	58
		TGCTCTAACCAGCAGCTGAACT	Rev	
Dsg2	XM_040664387.2	AAGCTGTCTCTTTTGCGGAAGA	For	73
		TCCCCCTGAGAATAAACCAGAA	Rev	
Dsg4	XM_040664432.2	CGTGCAATACTCCAGCCAGTAA	For	73
		GCTAATAAGTGTTGGTGCAAGTTTCA	Rev	
Dsc1	XM_040664420.2	TGGATTATGAAAATGCCAAACAA	For	67
		AGCATGTAGGGTGCCTCATTG	Rev	

[a]AFDN, afadin; CDH2, cadherin 2; CGN, cingulin; CLDN, claudin; CTNNA2, Catenin α2; CTNNB1, Catenin β1; DSC1, desmocollin 1; DSG2, desmoglein 2; DSG4, desmoglein 4; GJA3, gap junction protein α3; GJB1, gap junction protein β1; GJC2, gap junction protein γ2; GJD2, gap junction protein δ1.
[b]Accession number refers to GenBank (National Center for Biotechnology Information–NCBI).

Winooski, VT). Proteins were separated on 4%–12% Bis-Tris gels (Life Technologies, Carlsbad, CA), and transferred to PVDF membranes. Membranes were blocked with 5% non-fat milk in TBS-T for 1 h at room temperature, then incubated with primary antibodies overnight at 4°C. Primary antibodies used were rabbit anti-claudin 4 (CLDN4, 1:1,000, bs-2790R, Bioss, Woburn, MA), rabbit anti-CLDN5 (1:1,000, sc-28670, Santa Cruz Biotechnology, Dallas, TX), and anti-rabbit zona occluding-2 (ZO-2, 1:1,000, 38–9,100, ThermoFisher Scientific, Waltham, MA). Rabbit anti-Glyceraldehyde 3-phosphate dehydrogenase (GAPDH, 1:1,000, NB300-327, Novus Biologicals, Centennial, CO) was used as a loading control. Horseradish peroxidase (HRP)-conjugated secondary antibody (goat anti-rabbit IgG #7074, Cell Signaling, Danvers, MA) was used at 1:5,000 dilution for 1 h at room temperature. The signal was visualized by chemiluminescence (SuperSignal West Femto Maximum Sensitivity Substrate, ThermoFisher Scientific, Waltham, MA) and captured by FluorChem M MultiFluor System (ProteinSimple, Santa Clara, CA). Image acquisition and analysis were performed with AlphaView software (version 3.4.0.0, ProteinSimple, Santa Clara, CA).

2.5 Statistics

Gene and protein expression data (n = 12/line/environment) were analyzed by two-way ANOVA. When ANOVA revealed significant interaction effects, the means were compared by Tukey's HSD multiple comparison test. If the line by environment interaction was not significant, the main effect (Line, L or Environment, E) was analyzed separately by Student's t-test test using Graph Pad Prism version 9.00 for Windows (Graph Pad Software, La Jolla California, USA). Data are presented as the mean ± standard error of the mean and the statistical significance was set at $P < 0.05$.

3 Results

3.1 Intestinal permeability is decreased in HWE as compared to LWE broilers

As measured by FITC-D in serum, intestinal permeability was lower in the HWE as compared to the LWE birds (P = 0.0009, Figures 1A, B). There was no overall effect of HS (Figure 1A).

3.2 Differential expression of tight junction proteins in heat-stressed LWE and HWE broilers

For the barrier-forming claudins, CLDN5 protein levels were significantly decreased by HS compared to TN conditions (Figures 2A–C). The expression of *Cldn5* gene, however, was upregulated in LWE, and downregulated in HWE under HS conditions, which resulted in a significant line by environment interaction (Figure 2D). The expression of *Cldn1* gene was significantly upregulated in the ileum of HWE birds compared to their LWE counterparts (Figures 2E, F). *Cldn20* mRNA abundances were induced by HS only in LWE but not in HWE birds, resulting in a significant line by environment interaction (Figure 2G). Heat stress downregulated *Cldn25* gene expression in LWE and *Cldn34* in HWE birds, causing a significant line by environment interactions (P = 0.0367 and P = 0.0475 for *Cldn25* and *Cldn34*, respectively, Figures 2H, I). There was no significant effect of line or of HS on the ileal expression of *Cldn8*, *Cldn9*, and *Cldn22* (Table 2).

Among the pore-forming claudins, *Cldn4*, *Cldn15*, and *Cldn16* were differentially regulated. *Cldn4* gene expression was affected by both line and environment, where mRNA abundances were increased in the HWE line (P = 0.0330) and decreased in HS condition (P = 0.0138, Figures 3D–F). CLDN4 protein levels were significantly reduced by HS (Figures 3A–C), although the overall effect of line was not statistically and significantly discerned (P = 0.3548). The expression of *Cldn15* gene was higher in the HWE line under TN conditions, and significantly downregulated by HS in the same line, but not in the LWE counterparts (P = 0.0043, Figure 3G), resulting in a significant line by environment interaction (P = 0.0105). The expression of *Cldn16* gene was upregulated by HS in the LWE and downregulated in the HWE, with a significant line by environment interaction (P = 0.0384, Figure 3H). There were no significant effects of line nor environment on *Cldn2*, *Cldn19*, or *Cldn23* (Table 2).

Protein levels of ZO-2 were significantly decreased by HS only in HWE but not in LWE birds, which resulted in a significant line by environment interaction (Figures 4A, B). The gene expression of *Zo-2* remained unchanged (Figure 4C). Cingulin (*Cgn*) gene expression was affected by both line and environment (Figures 4D–F), where it was lower in HWE as compared to LWE (P = 0.0006) and lower in HS as compared to TN (P = 0.0018). The expressions of Occludin (*Ocln*), zona occludin-3 (*Zo-3*), PALS1-associated tight junction protein (*Patj*), and junctional adhesion molecule A (*Jam-A*) genes were all unaffected by line or environmental conditions (Table 2).

3.3 Differential expression of gap junction gene expression in LWE and HWE broilers during HS

Abundances of the gap junction protein α1 (*Gja1*) mRNA were affected by line, with a significant increase in the HWE as compared to the LWE birds under both environmental conditions (P = 0.0258, Figures 5A, B). There were no effects of line nor environment on gene expression of gap junction protein α3 (*Gja3*), gap junction protein β1 (*Gjb1*), gap junction protein γ1 (*Gjc1*), gap junction protein γ2 (*Gjc2*), or gap junction protein δ1 (*Gjd2*) (Table 2).

3.4 Differential expression of adherens junction gene expression in LWE and HWE broilers during HS

There was a significant line by environment interaction effect on cadherin 1 (*Cdh1*, P = 0.0394, Figure 6A) and Catenin α2 (*Ctnna2*, P = 0.0243, Figure 6B) gene expression. Cadherin one expression was higher in HWE birds under TN condition and was downregulated by HS exposure (Figure 6A). Catenin α2 expression was induced by HS only in the ileum of HWE birds (Figure 6B). There were no

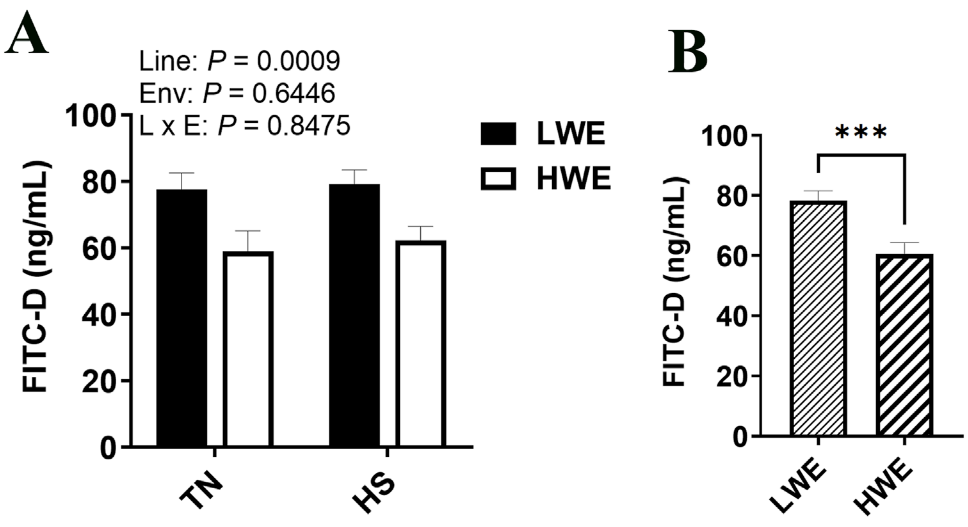

FIGURE 1
Effect of heat stress on serum FITC-D levels in LWE and HWE chickens. **(A, B)** Data were analyzed by two-way ANOVA and are presented as mean ± SEM (n = 12 birds/group). When the line by environment interaction was not significant, the main effect was analyzed separately by Student's *t*-test.***indicates significant difference at $P < 0.001$. E and Env, environment; HS, heat stress; HWE, high water efficient; L, line; LWE, low water efficient; TN, thermoneutral.

significant effects of HS nor line on cadherin 2 (*Cdh2*), Catenin β1 (Ctnnb1), Nectin1, or afadin (*Afdn*) (Table 2).

3.5 Differential expression of desmosome gene expression in LWE and HWE broilers during HS

Gene expression of desmoglein 4 (*Dsg4*) was increased in the HWE line as compared to the LWE ($P = 0.0497$, Figures 7A, B). There was an interactive effect of line and environment on desmocolin 1 (*Dsc1*), where gene expression was increased by HS only in the HWE line ($P = 0.0382$, Figure 7C). There was no significant effect of HS nor line on desmoglein 2 (*Dsg2*) gene expression (Table 2).

4 Discussion

Maintenance of intestinal barrier integrity is critical to organismal health and allows selective permeability of transport of ions, nutrients, and water while restricting pathogens (Rescigno, 2011). Over 80 proteins have been identified as contributing to this barrier, with distinct as well as coordinated functions (Tsukita et al., 2001). A key point, however, is that none of these tight junctions, adherens junction, gap junctions, and desmosome proteins work in isolation. The complex constantly adapts to changes in the biological state through constant remodeling and intracellular trafficking, where proteins are inserted and internalized from the membrane (Shen et al., 2008). Together, they form a well-organized matrix to provide a barrier that is both functional and efficient. Here, regardless of temperature, the HWE birds displayed lower intestinal permeability, as measured by serum FITC-D, compared to the LWE line. As the intestinal barrier integrity is controlled by a complex network of tight junction, gap junction, and desmosomes, here we sought to further assess the expression of barrier integrity-related genes in these two lines of birds under HS conditions.

Claudins are tight junction proteins that can be broadly classified into two categories: barrier-forming and channel- or pore-forming. The barrier-forming claudins restrict the passage of small molecules and electrolytes, whereas the pore-forming claudins allow the passage of ions and water through paracellular channels (Krause et al., 2008). One of the first claudins isolated (Furuse et al., 1998), CLDN1 is highly expressed across the entire intestinal tract, and downregulation of CLDN1 has been shown to be associated with increased intestinal permeability *via* the NFκB pathway (Zhou et al., 2015). Here, the *Cldn1* gene was increased in the ileum of the HWE birds as compared to their LWE counterparts, which likely contributes to the improvements seen in intestinal permeability in this line. Additionally, chronic stress has been associated with decreased intestinal CLDN1 (Zheng et al., 2017). CLDN1 was not significantly affected by HS in the current study, which might indicate an adaptation to the chronic (20 days) HSs. *Cldn5* and *Cldn20* genes showed similar patterns of expression in the two studied lines, with increased expression in the LWE line and decreased expression in the HWE during HS. As barrier-forming claudins, increased expression of these genes tends to decrease membrane permeability (Rahner et al., 2001; Martin et al., 2013), which is supported by the downregulation of *Cldn5* in HS conditions. However, little is known about their function in the avian intestine. CLDN5 is tightly regulated at the blood-brain-barrier and is compromised in several neurological diseases (Hashimoto et al., 2023), while in breast-cancer models, overexpression of CLDN20 increases trans-epithelial electrical resistance (TEER) (Martin et al., 2013), both tissue-specific roles highlighting the complex nature

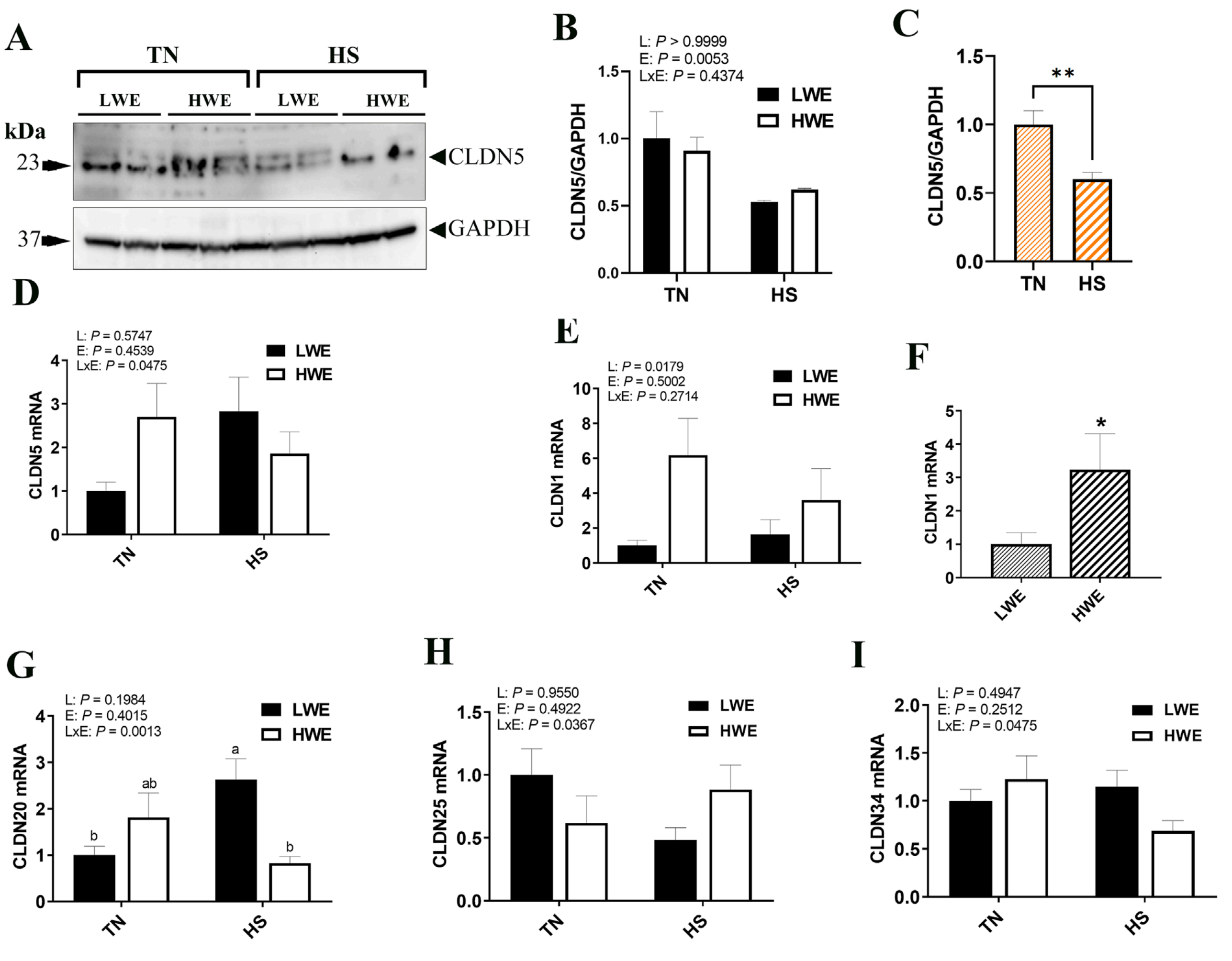

FIGURE 2
Effect of heat stress on the expression of barrier-forming claudins in LWE and HWE chickens. Protein expression of CLDN5 was determined by Western blot. **(A–C)** Gene expression of CLDN5 **(D)**, CLDN1 **(E, F)**, CLDN20 **(G)**, CLDN25 **(H)**, and CLDN34 **(I)** were measured by qPCR. Data were analyzed by two-way ANOVA and are presented as mean ± SEM (n = 12 birds/group). When the line by environment interaction was not significant, the main effect was analyzed separately by Student's *t*-test. Different letters indicate significant differences at $P < 0.05$.*and**indicate significant difference at $P < 0.05$ and $P < 0.01$, respectively. CLDN, claudin; HS, heat stress; HWE, high water efficient; LWE, low water efficient; TN, thermoneutral.

of claudins. Similarly, the function of CLDN25 has yet to be fully understood. A paralog of CLDN22, CLDN25 does not seem to be either directly barrier- or pore-forming; however, its role in barrier regulation seems to depend on the composition of other claudins within the tight junction (Hashimoto et al., 2024). This is supported by evidence of differential effects in different cell types *in vitro*. In mouse brain endothelial cells (bEnd.3), CLDN25 knockout lowered solute permeability, while it increased in Madin-Darby canine kidney strain II (MDCKII) cells. However, TEER was increased in both cell types. Future functional studies are necessary to delineate the function of CLDN25 in the chicken intestine. Likewise, CLDN34 is understudied in both mammalian and avian species. Based on studies in fish, enhanced intestinal expression is related to enhanced immune function, whether in response to a bacterial challenge (Cao et al., 2023) or a dietary immunomodulator (Zhang et al., 2024). Taken together, these data suggest that differential expressions of the barrier-forming claudins are integral components of the differences seen in water efficiency selected broilers; however, further research is necessary to delineate the functions of individual claudins, as well as their interaction in poultry intestine.

Multiple pore-forming claudins are also differentially regulated between the two lines. CLDN2, 10b, 15, 16 and 21 have been shown to form cation-selective paracellular channels, whereas CLDN10a and 17 are understood to form anion-selective channels (Günzel and Yu, 2013). Of particular interest to this work, CLDN2 and 15 are known to move water as well as other solutes such as sodium and potassium (Rosenthal et al., 2020; Samanta et al., 2018). Interestingly, *Cldn2* gene was unaffected in this study; however, its protein expression and localization within the gut are known to be negatively regulated by *Cgn* (Guillemot et al., 2012), a gene that was lower in the HWE line. *Cldn15* showed a greater mRNA expression in the HWE line, particularly under the TN environment. Together, these may be significant contributing factors to the improved water efficiency in this line, as water uptake at the small intestine may be more easily facilitated. Interestingly, CLDN15 also indirectly

TABLE 2 Relative expression of ileal integrity-associated genes in heat-stressed LWE and HWE broilers.

Environment[a]	TN		HS		*P* value		
Gene[b]/Line[c]	LWE	HWE	LWE	HWE	L	E	L x E
Barrier-forming CLDNs							
Cldn8	1 ± 0.20	2.24 ± 0.75	2.16 ± 0.63	2.01 ± 0.82	0.4476	0.5205	0.3395
Cldn9	1 ± 0.17	1.38 ± 0.41	1.62 ± 0.58	1.30 ±0.38	0.9475	0.5294	0.4181
Cldn22	1 ± 0.14	1.91 ± 0.68	1.47 ± 0.24	1.85 ± 0.42	0.1429	0.6330	0.5357
Pore-forming CLDNs							
Cldn2	1 ± 0.33	0.81 ± 0.32	0.75 ± 0.27	0.73 ± 0.20	0.7169	0.5799	0.7786
Cldn19	1 ± 0.24	1.09 ± 0.27	1.31 ± 0.33	0.79 ± 0.22	0.4528	0.9777	0.2713
Cldn23	1 ± 0.09	1.02 ± 0.11	0.74 ± 0.05	0.94 ± 0.07	0.2270	0.0682	0.3557
Other TJ proteins							
ZO-3	1 ± 0.32	5.11 ± 2.20	1.81 ± 0.76	2.53 ± 1.11	0.6883	0.1208	0.4323
Ocln	1 ± 0.29	1.06 ± 0.27	0.91 ± 0.27	0.48 ± 0.06	0.4613	0.1812	0.3171
Patj	1 ± 0.44	2.17 ± 0.72	1.14 ± 0.27	1.95 ± 1.28	0.2671	0.9697	0.8402
Jama	1 ± 0.37	2.21 ± 0.84	1.35 ± 0.82	0.50 ± 0.14	0.7788	0.2938	0.1123
Gap junctions							
Gja3	1 ± 0.14	1.65 ± 0.57	1.71 ± 0.22	2.15 ± 0.56	0.2009	0.1627	0.8032
Gjb1	1 ± 0.14	0.93 ± 0.24	0.91 ± 0.12	1.18 ± 0.25	0.6212	0.6882	0.4334
Gjc1	1 ± 0.30	3.73 ± 1.25	2.62 ± 0.92	2.52 ± 0.77	0.1577	0.8193	0.1306
Gjc2	1 ± 0.11	1.21 ± 0.31	1.10 ± 0.23	0.69 ± 0.16	0.6540	0.3557	0.1659
Gjd2	1 ± 0.19	1.22 ± 0.40	1.13 ± 0.23	1.98 ± 0.58	0.1823	0.2667	0.4414
Adherens							
Cdh2	1 ± 0.17	1.36 ± 0.27	1.01 ± 0.18	1.12 ± 0.18	0.2779	0.6007	0.5400
Ctnnb1	1 ± 0.09	0.81 ± 0.07	1.01 ± 0.08	1.01 ± 0.07	0.2634	0.2071	0.2990
Nectin1	1 ± 0.08	0.97 ± 0.11	1.16 ± 0.12	0.94 ± 0.07	0.2601	0.5185	0.3590
Afdn	1 ± 0.21	0.92 ± 0.16	1.00 ± 0.12	1.24 ± 0.26	0.6852	0.4217	0.4352
Desmosomes							
Dsg2	1 ± 0.19	1.42 ± 0.28	1.18 ± 0.12	1.30 ± 0.25	0.4857	0.8842	0.2312

[a]HS, heat stress; TN, thermoneutral.
[b]*Afdn*, afadin; *Cdh2*, cadherin 2; *Cldn*, claudin; *Ctnnb1*, beta-catenin; *Dsg2*, desmoglein; *Gja3*, gap junction protein alpha 3; *Gjb1*, gap junction protein beta 1; *Gjc1*, gap junction protein gamma 1; *Gjd2*, gap junction protein delta 2; *Jama*, junctional adhesion molecule A; *ocln*, occludin; *Patj*, PALS1-associated tight junction protein; *Z O -3*, Zonula occludens protein 3.
[c]HWE, high water efficient; LWE, low water efficient.

enhances glucose uptake *via* Na^+ flux into the lumen of the intestine and subsequently enhances the activity of Na^+-driven glucose transporter SGLT1 (Tamura et al., 2011), an additional role that may be impacting the BWG and FCR improvements seen in the HWE line (Aloui et al., 2024). CLDN16 is recognized for its role in calcium transport, as mutated CLDN16 may be responsible for defective absorption of Ca^{2+} along the intestine (Weber et al., 2001). Although calcium metabolism has yet to be explored in these lines

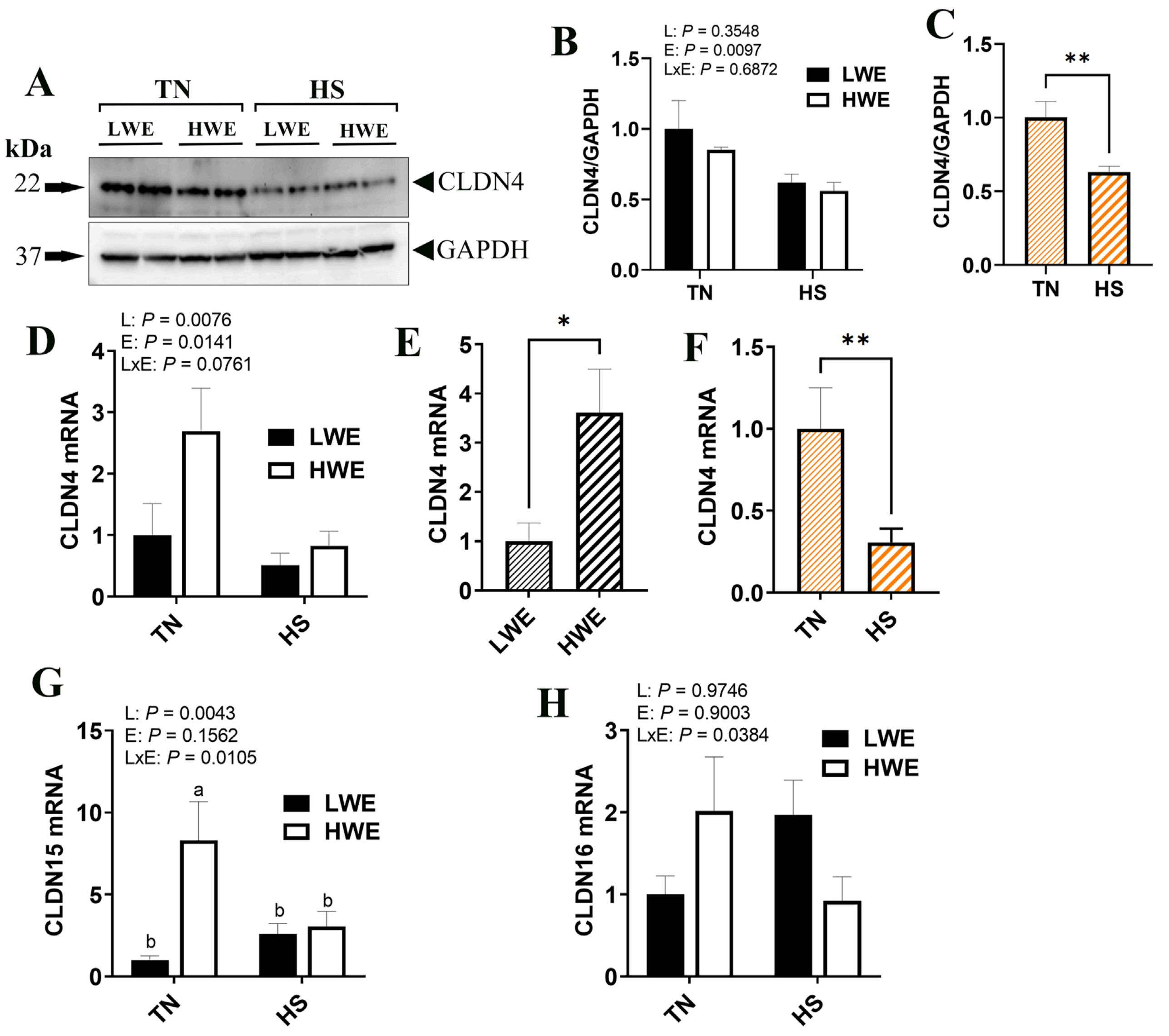

FIGURE 3
Effect of heat stress on the expression pore-forming claudin expression in LWE and HWE chickens. Protein expression of CLDN4 was determined by Western blot. **(A–C)** Gene expression of CLDN4 **(D–F)** CLDN15 **(G)**, and CLDN16 **(H)** were measured by qPCR. Data were analyzed by two-way ANOVA and are presented as mean ± SEM (n = 12 birds/group). When the line by environment interaction was not significant, the main effect was analyzed separately by Student's *t*-test. Different letters indicate significant differences at $P < 0.05$.*and**indicates significant difference at $P < 0.05$ and $P < 0.01$, respectively. CLDN, claudin; HS, heat stress; HWE, high water efficient; LWE, low water efficient; TN, thermoneutral.

of birds, it is plausible, based on the differential expression of *Cldn16* due to line × environment interaction, observed here, that these lines had different Ca^{2+} transport, absorption, and/or metabolism. Additionally, in chickens, CLDN16 has been localized to goblet cells, suggesting a further role in mucus secretion (Ozden et al., 2010) and thereby homeostasis of intestinal flora. CLDN4 has a unique function, as it is considered pore-forming regulating, as it can interfere with and regulate CLDN2, 7, 15, and 19, and increase the complexity of tight junctions (Van Itallie et al., 2001; Shashikanth et al., 2022a; Shashikanth et al., 2022b), a role which may be indicated in the increased expression in the HWE line. Downregulation of CLDN4 has been seen in areas of intestinal inflammation (Prasad et al., 2005), which is likely reflected here in the lower expression seen in HS, regardless of line. Although the role and regulation of avian ZO-2 are not well known, its ileal downregulation by HS exposure, at least in HWE line here opposed that in the duodenum of broilers from the 1990s (Tabler et al., 2020), which suggests a tissue- or strain-specific regulation (Santos et al., 2021). Based on previous studies showing that rye diet alters gut integrity and induces leaky gut syndrome in broilers (Baxter et al., 2019), and this was accompanied by an upregulation of ileal ZO-2, it is logical to postulate that ZO-2 downregulation in our study supports a better gut integrity in HWE line.

Gap junctions are important in cell structure as well as for cell-to-cell communication *via* the transfer of ions and small molecules between adjacent cells (Wong et al., 2019). Gap junction genes

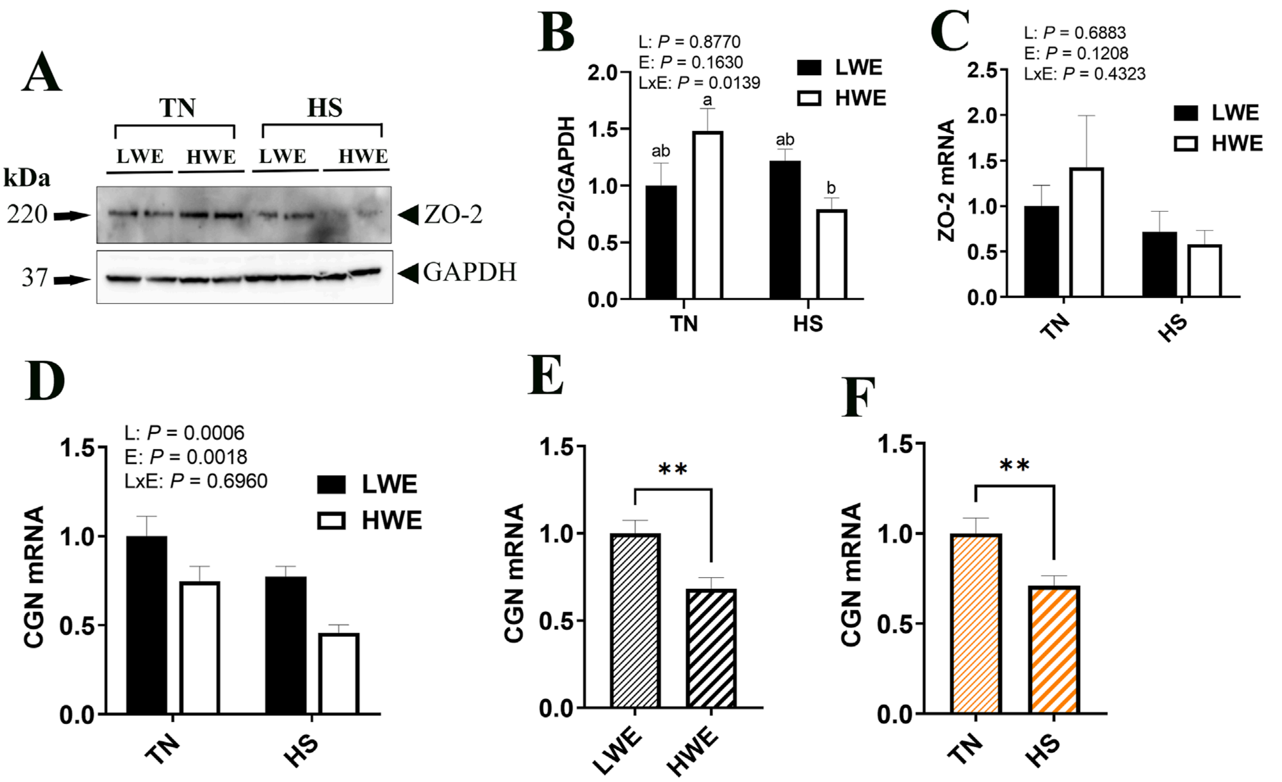

FIGURE 4
Effect of heat stress on tight-junction gene expression in LWE and HWE chickens. Protein expression of Zo-2 was determined by Western blot **(A, B)**. Gene expression of ZO-2 **(C)** and CGN **(D–F)** was measured by qPCR. Data were analyzed by two-way ANOVA and are presented as mean ± SEM (n = 12 birds/group). When the line by environment interaction was not significant, the main effect was analyzed separately by Student's *t*-test. Different letters indicate significant differences at $P < 0.05$.**indicates significant difference at $P < 0.01$. CGN, cingulin; HS, heat stress; HWE, high water efficient; JAM-A, junctional adhesion molecule A; LWE, low water efficient; OCDN, occludin; PATJ, protein associated to tight junctions; TN, thermoneutral; ZO, zona occludin.

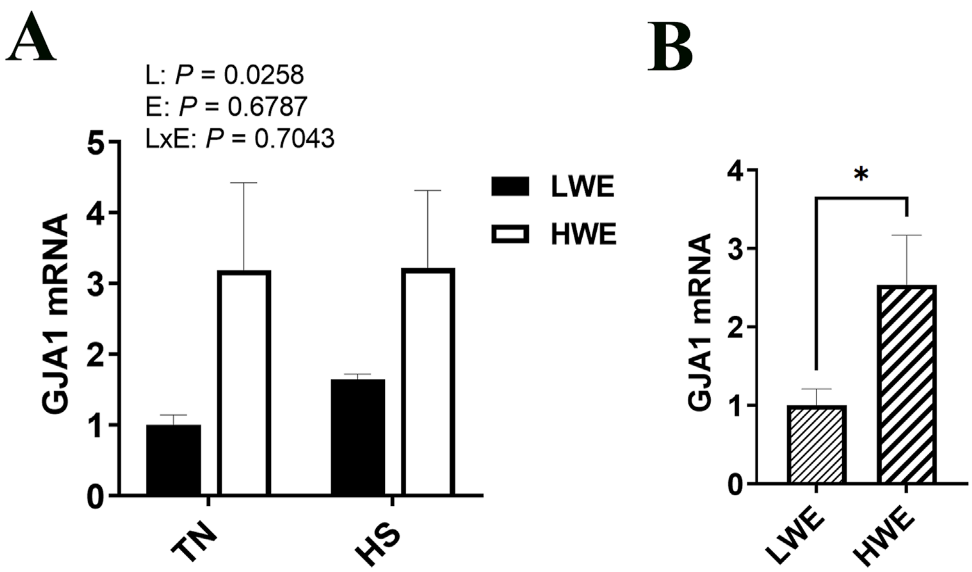

FIGURE 5
Effect of heat stress on GJA1 gene expression in LWE and HWE chickens. Gene expression of GJA1 **(A, B)** was measured by qPCR. Data were analyzed by two-way ANOVA and are presented as mean ± SEM (n = 12 birds/group). When the line by environment interaction was not significant, the main effect was analyzed separately by Student's *t*-test.*indicates significant difference at $P < 0.05$. GJA, gap junction protein α; HS, heat stress; HWE, high water efficient; LWE, low water efficient; TN, thermoneutral.

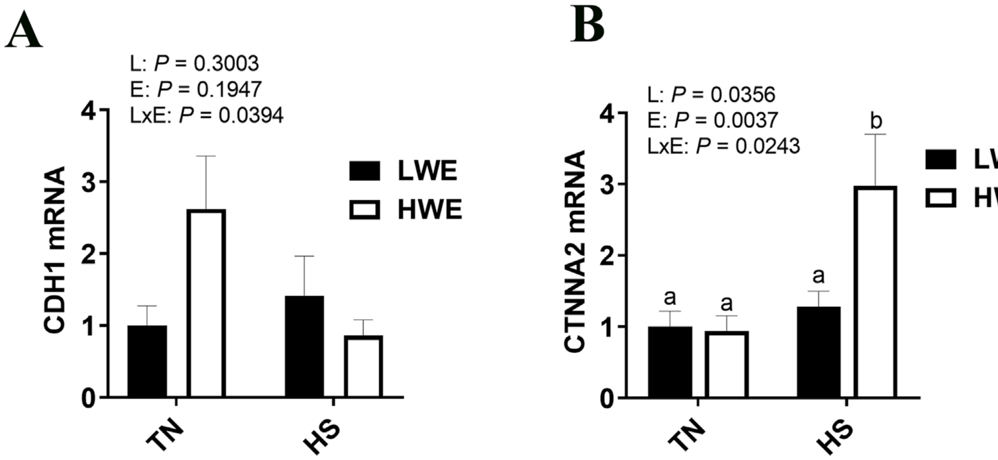

FIGURE 6
Effect of heat stress on CDH1and CTNNA2 gene expression in LWE and HWE chickens. Gene expression of CDH1 **(A)** and CTNNA2 **(B)** was determined by qPCR. Data were analyzed by two-way ANOVA and are presented as mean ± SEM (n = 12 birds/group). CDH, cadherin; CTNNA2, catenin α2; HS, heat stress; HWE, high water efficient; LWE, low water efficient; TN, thermoneutral.

encode connexins, which are differentially and widely expressed throughout the body. Here, among the gap junction genes, only *Gja1* (encoding connexin 43) was differentially expressed, and was higher in the HWE line. GJA1 plays multiple roles in intestinal epithelial health that may be influencing the physiology of the HWE line. First, GJA1 likely impacts intestinal motility *via* interaction with intestinal nerve transmission (Daniel et al., 2001; Daniel and Wang, 1999), as well as its function as a necessary component for motile cilia (Jang et al., 2022). In these broilers, it may be altering motility or gastrointestinal transit time in such a manner that could be influencing increases in water and nutrient absorption and contributing to the water efficiency, BWG, and FCR improvements seen in the HWE line (Aloui et al., 2024). However, digestibility studies have yet to be conducted in these birds, so this remains speculative. Second, connexin 43 is redistributed within intestinal epithelial cells to the basolateral surface during inflammation (as seen in inflammatory bowel disease) (Al-Ghadban et al., 2016), and it has been shown to be associated with inflammasome (de)activation (Roger et al., 2023). The higher expression of *Gja1* here and the downregulation of *Nlrc3* in HWE blood (Greene et al., 2024), suggest that GJA1 might improve the gut inflammatory status of HWE line, resulting in better barrier integrity and better growth performance. In addition, connexins have a short half-life of only a few hours (Segretain and Falk, 2004), so investigating the spatio-temporal nature of their responses to HS in poultry gut is warranted.

Adherens junctions organize and stabilize the condensed actin filaments of the cytoskeleton with the plasma membrane and are assembled from classical cadherins, armadillo proteins, and cytoskeletal adaptor proteins (Harris and Tepass, 2010). E-cadherin (encoded by *Cdh1*) is the most crucial cadherin present on the epithelial surface responsible for adherens junction formation *via trans* adhesive homodimers with other cadherins (Gumbiner, 2005; Brasch et al., 2012). Among the cadherins studied, we saw differential regulation of Cdh1, which was greater in the HWE in TN conditions, but lower under HS. Others have reported increases in *CDH1* in poultry intestine in response to HS; however, the response is likely region-specific, with increases seen in the jejunum, but not in the ileum (Varasteh et al., 2015). Cadherins bind to catenins as part of the stabilization structure, and in particular, α-catenin binds to the E-cadherin/β-catenin complex (Drees et al., 2005). The dimerization of CTNNA2 influences binding to other proteins; monomeric α-catenin binds β-catenin, but not actin, while homodimeric α-catenin binds actin but not β-catenin (Yamada et al., 2005). In this way, it helps regulate microtubule dynamics and has been shown to play a central role in cytoskeletal rearrangement in response to extracellular events (Perez-Moreno and Fuchs, 2006; Arbore et al., 2022). In a fish model, increased methylation on *Ctnna2* was associated with increased intestinal integrity and decreased inflammation (Dhanasiri et al., 2020). Interestingly, *Ctnnna2* expression is also associated with climate adaptation in mediterranean cattle (Flori et al., 2019). As this gene was upregulated only during HS in the HWE line, it may serve a role in helping stabilize the adherens junction, as other components (particularly the cadherins) are unchanged or downregulated as compared to TN conditions.

Desmosomes are the least well studied of the epithelial barrier regulating proteins, but have been shown to create strong intercellular adhesion, particularly in tissues subject to mechanical stress. Intercellular adhesion is normally initiated by adherens junctions, then stabilized by desmosomes *via* connecting intermediate filaments to the plasma membrane (Vasioukhin et al., 2000). Desmogleins form heterodimers with desmocollins (Getsios et al., 2004), and one of the strongest binding has been found between DSC1 and DSG4 (Harrison et al., 2016), both of which show greater expression in the HWE during HS, which is likely contributing to increased intestinal integrity and lower leaky gut. Desmosomes also can exist in two adhesive states, a weaker, Ca^{2+} dependent state, and a stronger, Ca^{2+} independent state termed "hyperadhesion". This hyperadhesion is critically important in the ability of cells to

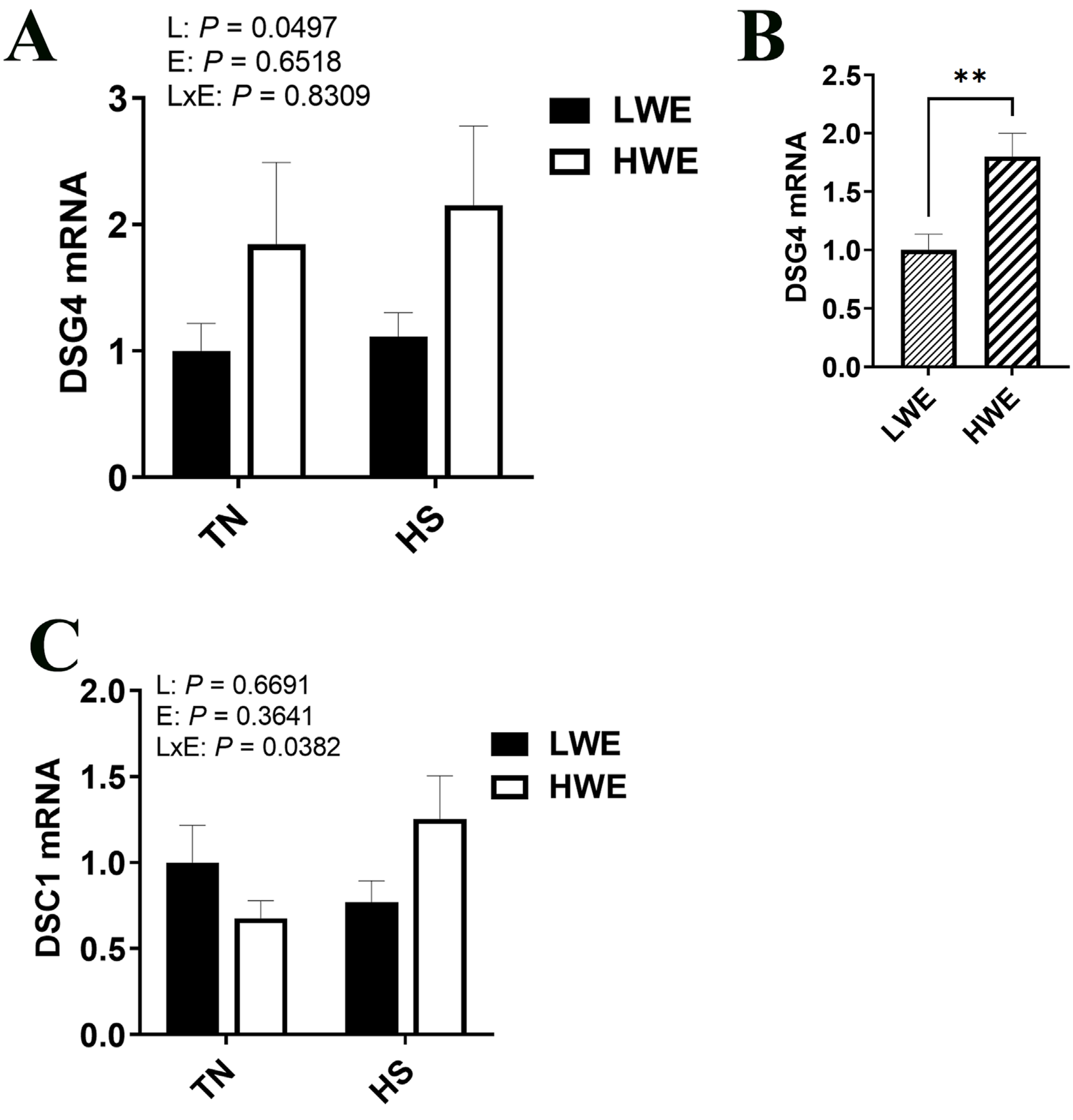

FIGURE 7
Effect of heat stress on desmosome gene expression in LWE and HWE chickens. Gene expression of DSG4 **(A, B)** and DSC1 **(C)** was measured by qPCR. Data were analyzed by two-way ANOVA and are presented as mean ± SEM (n = 12 birds/group). When the line by environment interaction was not significant, the main effect was analyzed separately by Student's *t*-test.**indicates significant difference at $P < 0.01$. DSC1, desmocollin 1; DSG, desmoglein; HS, heat stress; HWE, high water efficient; LWE, low water efficient; TN, thermoneutral.

resist shear forces that would separate cells and disrupt tissues (Garrod and Tabernero, 2014; Beggs et al., 2022). Protein Kinase C (PKC) pathways, which have been shown to be induced by HS (Yang et al., 2007), negatively regulate hyperadhesion (Garrod et al., 2008), a further mechanism by which HS can impact intestinal barrier integrity.

It is interesting to note that both serum FITC-D and many of the measured genes are minimally affected by HS in either line. As these birds were subject to cyclic HS for 20 days, it is plausible that some of the responses are reflective of adaptation to the environmental challenge. It is also plausible that birds were recovered during the cool phase. As the HWE, overall, responded more favorably to HS (in terms of decreased intestinal permeability, and increased growth, water and feed efficiency), it may be that the genes associated with intestinal integrity in the LWE are upregulated to try to fix or improve the disrupted barrier, while the HWE were overall more resilient. It is also possible that although gene and/or protein levels of the tight junctions are unaffected, post-translational modifications (Shigetomi and Ikenouchi, 2017) or distribution/localization within the cell, and therefore function, may be affected by genetics or HS. Indeed, this has been seen in other models, including Llc-Pk1 kidney cells (Ikari et al., 2005), Caco-2 intestinal epithelial cells (Han et al., 2003), and isolated T cells (Voges et al., 2024), and warrants further investigation in these lines.

Overall, these results provide further evidence for the positive potential of water efficiency selection in poultry, as there were improvements in intestinal integrity over the LWE line, with no additional impairments due to HS. In addition, differential gene expression of intestinal barrier proteins may help delineate some of the underlying mechanisms of improved water efficiency and identify potential markers for further selection.

Data availability statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Ethics statement

The animal study was approved by the University of Arkansas Animal Care and Use Committee. The study was conducted in accordance with the local legislation and institutional requirements.

Author contributions

EG: Formal Analysis, Writing–original draft. BR: Data curation, Formal Analysis, Writing–original draft. MC: Data curation, Formal Analysis, Writing–original draft. SO: Data curation, Formal Analysis, Writing–original draft. SD: Conceptualization, Funding acquisition, Project administration, Supervision, Visualization, Writing–review and editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The author(s) declare that no Generative AI was used in the creation of this manuscript.

Publisher's note

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Education necessity for veterinary-producer relationship creation and sustainability: a mixed method study

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Objectives: To identify barriers to veterinarian-producer partnerships and suggest collaborative applied education as a means to enhance economic efficiency and sustainability of small and medium livestock operations and rural veterinary practices.

Materials and methods: A participatory needs assessment, exploring the willingness and barriers to producer-veterinarian partnerships to enhance small/medium livestock operations, was distributed to Texas producers and veterinarians. Quantitative and qualitative data were collected via online, closed-ended survey questions and free response interviews. Responses were analyzed using SPSS and *HyperRESEARCH* to identify relevant terms, ideas, patterns, or themes.

Results: Similar responses from 115 veterinarians and 58 producers revealed five major themes regarding relationship barriers: time, financial challenges, communication, competing perspectives, and respect. Overall producers reported greater willingness to partner in all areas, health care (90%), to achieve goals (80%), and to expand business (70%), than veterinarians. Veterinarian interviews revealed a need for increased animal health education among producers, while more than 60% of producers expressed high interest in continuing education on animal health topics.

Discussion: Veterinarians and producers experience similar barriers to establishing partnerships. Both groups also recognize a need for education and prefer in-person collaborative learning communities Such educational opportunities can encourage formal veterinary-producer partnerships and provide solutions that enhance the economic efficiency and sustainability of small/medium livestock operations.

KEYWORDS

veterinarian-producer relationship, veterinary-producer perspectives, veterinary care barriers, education programs, partnership willingness, operation sustainability

1 Introduction

Strong veterinary-client relationships are the hallmark of thriving veterinary practices. Producers of small and medium-sized livestock operations, especially in rural areas, prove a particularly challenging population of clients for veterinarians to build and maintain relationships with. Limited research exists describing the obstacles impeding relationship

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development. However, extrapolation from publications related to veterinarian and producer interactions indicates producers' access to veterinary care, generational knowledge of producers, and the availability of veterinarians to provide service as prominent barriers. This research aims to clearly describe the challenges veterinarians and producers face in forming and sustaining partnerships and propose collaboratively led applied education programs as the means for creating, enhancing, and sustaining these relationships and the profitability of ranches and rural veterinary practices.

1.1 Access to veterinary care

Finances and negative perceptions limit access to veterinary care for producers of small and medium-sized livestock operations. Seeking veterinary care for individual animals is often determined by weighing perceived advantages against potential disadvantages (1). Does the animal's market value outweigh the expense of a farm call? Could self-treatment provide a more economic recovery route? Producers must consider profitability when managing their operations. Though producers and veterinarians view animal welfare as a priority, managing animal health varies based on differing perspectives on economics and priorities (2). Producers hesitate to pay for veterinary care they deem unnecessary or cost-prohibitive, whereas veterinarians describe their time, knowledge, services, and products as prescriptive and reasonably priced (3).

Historically, producers demonstrate a reluctance to utilize resources provided by local veterinarians. They felt their opinions were unimportant, that veterinarians were uninterested in their operational goals and sought to profit from their needs. These perceptions are supported by findings from Degroot et al. (4) noting veterinarians rarely ask producers about their broader attitudes, ideas, goals, values, or motivations in making decisions. Moreover, veterinarians tend to communicate in a paternalistic style, taking on an expert role, and not treating the producer as an equal partner in the conversation. They relied on giving information and persuasion without making an effort to grasp the client's perspective and experience (5). As a result, producers are disinclined to consult with veterinarians (6).

1.2 Generational knowledge

Multigenerational producers inherit not only the family farm but generations of knowledge regarding overall farm management, including care and treatment of livestock. Veterinary-producer relationships are hindered when producers use this generational knowledge to administer medications and vaccinations without consulting their veterinarian first (7). Veterinarians can assist producers in drug treatment options determined by an animal's age, weight, breed, and underlying health conditions. Additionally, they provide knowledge of dosing schedules, drug interactions, and withdrawal periods. Producers lacking this guidance may provide incorrect dosage, administration, or off-label use which can adversely affect animal health and marketability.

Further, many food and drug products require veterinary authorization or administration. One example is the Veterinary Feed Directive (VFD) for agricultural use, passed by the Food and Drug Administration in 2015 (8). This was implemented to reduce the unnecessary use of medications in animals and to slow or prevent the development of bacterial resistance to antimicrobial drugs administered within medicated feed (8). Creating prescription-only requirements for medications and feeds has required producers to create and maintain veterinary relationships while allowing veterinarians to engage with producers to sustain their veterinary practices (7). Data-driven advancements in veterinary medicine are more reliable than generational knowledge. Current educational resources supplied through a strong veterinary-client relationship will benefit producer knowledge, and thereby operation profitability and sustainability.

1.3 Availability to provide service

Between 2010 and 2020 America's rural population declined by 0.5%. Likewise, the number of farms decreased by 7% from 2017 to 2023 (9, 10). As a result, veterinary colleges face increasing difficulties retaining students with animal agriculture backgrounds most equipped to practice quality production medicine (11). Producers also prefer to partner with veterinarians who have strong farming backgrounds as they believe these individuals better understand the complexities of running a farm, as well as livestock medicine (12). Veterinarians must possess an in-depth knowledge of farm practices and business to earn the respect of producers (13). Additionally, many small and medium-sized farms support multiple species about which veterinarians may not be consistently knowledgeable. Hayes et al. (14) reported that a majority of veterinarians in their study population lacked confidence in treating multi-species due to insufficient exposure, experience, training, and/or knowledge.

Producers prefer to partner with veterinarians capable of making farm calls. However, veterinarians often find these visits impractical as they require specialized equipment and staff competent in handling livestock. Veterinarians lacking these resources are hindered in maintaining a rural practice (3).

In a study examining the sheep industry in the UK, researchers found that about two-thirds of ovine farmers only reach out to their veterinarian in the case of emergencies. They viewed veterinarians in the same regard as firefighters (15). Mindsets that include utilizing veterinary services only in emergencies, slow the development of trust and the creation of good partnerships (14), and thus the provision of services.

The current barriers between veterinarians and producers of small and medium-sized operations are ultimately the result of poor or non-existent relationships. To successfully develop these relationships there must be a renewed focus on understanding each other's goals, challenges, and expectations. We propose that collaborative education opportunities can surmount these barriers and enable livestock producers and rural veterinarians to create strong relationships leading to sustainability and profitability for both parties.

2 Methods

This mixed-methods study focused on producers of small livestock operations and veterinarians practicing mixed or large production animal medicine in Texas. Two online surveys with closed and open-ended questions (Appendix A) aimed to explore the willingness of and barriers to producers and veterinarians creating partnerships to enhance the profitability and sustainability of practices/operations.

Texas A&M AgriLife Extension Services and Prairie View A&M University's Cooperative Extension Program, an extension service whose mission is to respond to the needs of underserved Texans through learning opportunities that advance agriculture, promoted the producer's survey. To achieve a representative sample, West Texas A&M University (WTAMU) Extension, Waller County Farmers' & Ranchers' Cooperative, and 100 Ranchers, Inc. assisted in recruiting producers of color with small livestock operations. The producer's survey measured current and future interest in veterinarian partnerships, collected responses on the need for and awareness of local veterinarian services, and determined specific areas of educational need to maintain and sustain ranching operations.

Texas Veterinary Medical Association email listserv distributed the veterinarian survey. The veterinarian's survey measured current and future interest in producer partnerships, collected responses on the awareness of producers' needs and challenges, and determined specific areas of educational need to maintain and sustain local operations.

2.1 Data analysis

The closed-ended questions from veterinarian and producer surveys were analyzed using SPSS and the open-ended questions were analyzed using *HyperRESEARCH*. Open-ended responses were coded for keywords that aligned with question topics and identified areas of interest and research for this study. From the data reviews, a codebook was generated with clear definitions provided for each term or phrase. Codes that emerged during the data analysis were created to represent any term or idea that was deemed vital to the research (16). After reviewing the data, the researcher reflected upon the overall meaning of participant responses, identifying participant attitude and tone as well as patterns or themes. Results from the interpretation of the responses were represented using figures and tables and helped to inform further discussion of the findings.

3 Results

3.1 Quantitative survey responses

3.1.1 Participant demographics

The study included 95 veterinarians: 52% female and 48% male, with a median age of 53. The racial composition was 96% Caucasian, 3% Hispanic, and 1% American Indian. These veterinarians have an average of 26 years of experience and operate small, large, mixed, and food animal practices across 68 Texas counties. In comparison, 58 producers responded to the survey: 60% male and 40% female, also with a median age of 53. These participants had more diverse racial backgrounds: 65% African American, 29% Caucasian, 4% Hispanic, and 2% American Indian. The producers manage operations with seven unique species with an average of 25 years of experience. It is important to note that some operations surveyed produce more than one species. Notably, the two study groups were almost identical in median age and years of experience but had greater variance in race and gender. Reliability of the quantitative questions of the veterinarian survey yielded Cronbach's alpha = 0.85, while the producer survey yielded a Cronbach's alpha = 0.80.

3.1.2 Perspectives on service and information

Veterinarians significantly influence producers (17); however, not many veterinarians believe they do (14). Both groups of participants were asked about the services veterinarians offer and each group's perception regarding how most producers seek out information about animal health.

Veterinarians reported providing 14 unique services to producers ranging from vaccinations and treatment to record keeping and financial management. However, producers primarily knew of only the four most common services—vaccinations, examinations, treatment, and urgent care. The percentage of producers aware of any services outside these ranged from 0 to 6.4%.

Producers sought information from sources different from what the veterinarians perceived. Veterinarians expect only 24% of producers to seek their input about animal health questions when in reality twice that number, 48%, reported their veterinarian as their source of information for animal health. Veterinarians also expected producers to seek animal health information from the internet (22%) significantly more than the producers reported (6%). Figures 1 and 2 reveal the degree to which veterinarian and producer perspectives about available services and sources of animal health information are misaligned.

3.1.3 Partnership willingness

Veterinarians and producers were surveyed independently on their willingness to partner with one another to provide animal healthcare, grow their businesses, and achieve their business goals. Most veterinarians and producers were willing to partner with one another to provide animal healthcare. Figure 3 shows that over 60% of veterinarians and producers were somewhat or extremely likely to partner for animal healthcare. However, a t-test comparing the two groups demonstrated a statistically significant difference between veterinarians and producers (t (123) = 2.43, p = 0.02, Cohen's d = 0.43, CI [0.08, 0.80]). Producers (M = 4.34, SD = 0.87) were more willing to partner than veterinarians (M = 3.79, SD = 1.45) were willing to provide animal healthcare. Moreover, Figure 4 displays that most veterinarians (M = 3.61, SD = 1.34) and producers (M = 3.94, SD = 1.18) were willing to partner with one another to achieve their business goals. There was not a statistically significant difference found between the two group's willingness in this area [t (121) = 1.40, p = 0.16]. Across all three areas, producers reported more willingness to partner with veterinarians in all areas. Furthermore, most veterinarians and producers were willing to partner with one another to grow their businesses (see Figure 5). On the other hand, a t-test comparing the two groups demonstrated a statistically significant difference in willingness veterinarians (t (121) = 2.22, p = 0.03, Cohen's d = 0.41, CI [0.04, 0.77]). Producers (M = 3.67, SD = 1.39) were more willing to partner with veterinarians (M = 3.09, SD = 1.44) to grow their business than.

3.1.4 Self-assessment of knowledge

A literature review identified 10 animal health topics as possible avenues for veterinarians and producers to find common ground for developing partnerships. Veterinarians and producers indicated their

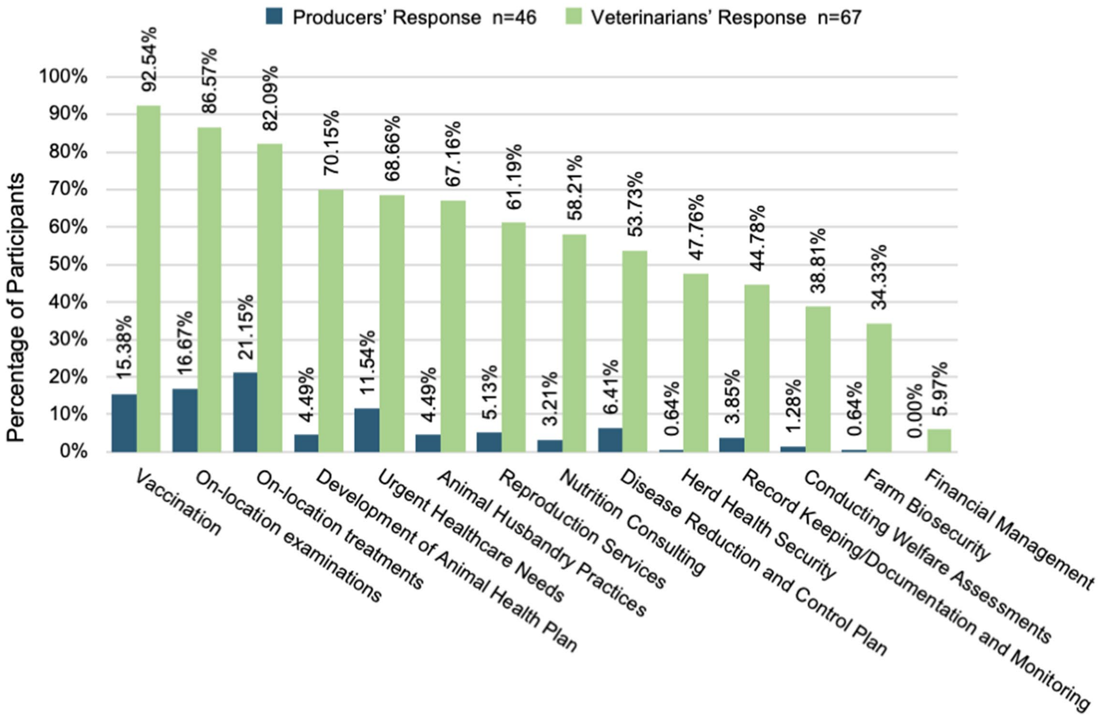

FIGURE 1
Perceived veterinary services offered.

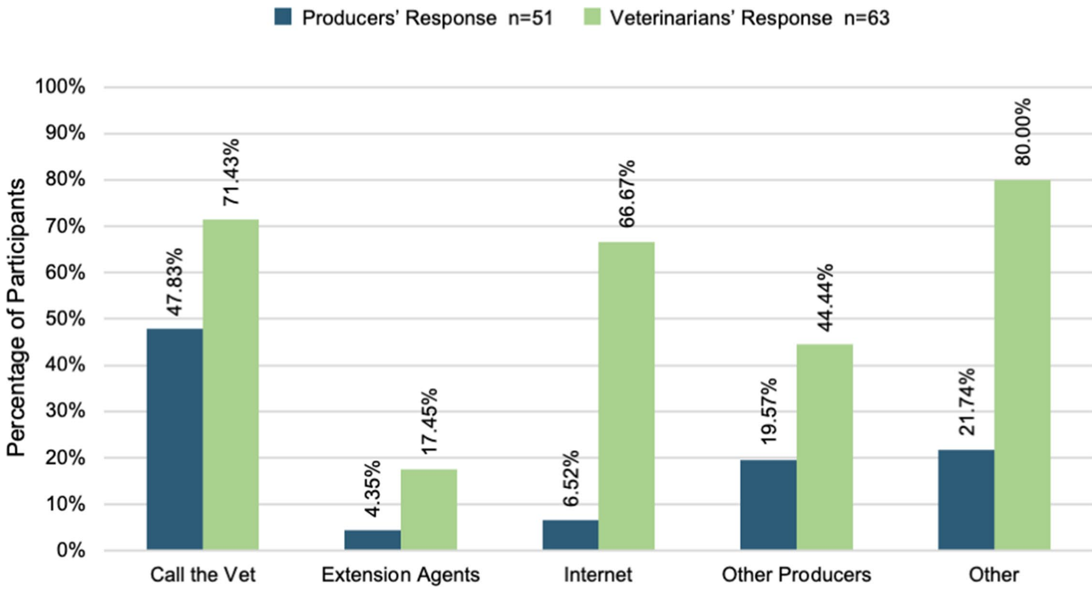

FIGURE 2
Animal health information sources.

current knowledge level on selected topics and producers indicated their interest in educational resources for these topics while veterinarians rated the impact such resources might have on the veterinary-producer relationship. Less than 40% of producers assessed their level of knowledge as "approaching mastery" or "master" for seven out of ten topics ("approaching" 13% ≥ x ≤ 32% and "master" 10% ≥ x ≤ 18%). However, a majority (63–81%) expressed a high level of interest in pursuing continuing education on all topics. Greater than 40% of veterinarians assessed their level of knowledge as "approaching mastery" or "master" for six out of ten topics ("approaching" 13% ≥ x ≤ 43% and "master" 10% ≥ x ≤ 39%). Most of their responses (46–79%) signified that continuing education in all topics would positively impact the veterinarian-producer relationship. Figures 6 and 7 describe these topics and participant responses.

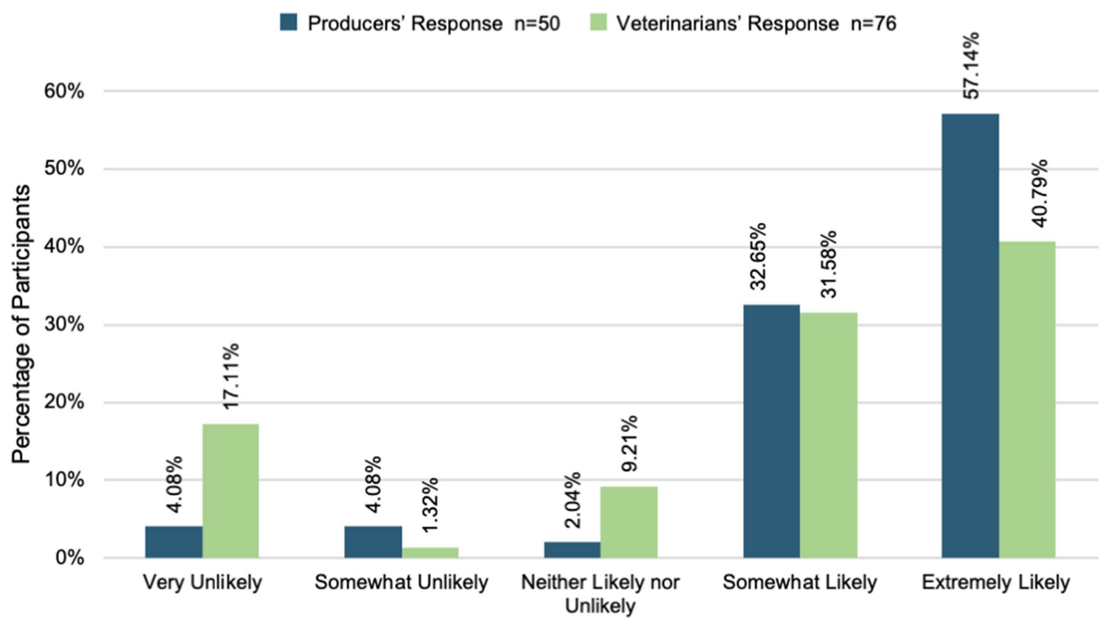

FIGURE 3
Willingness to partner for animal healthcare.

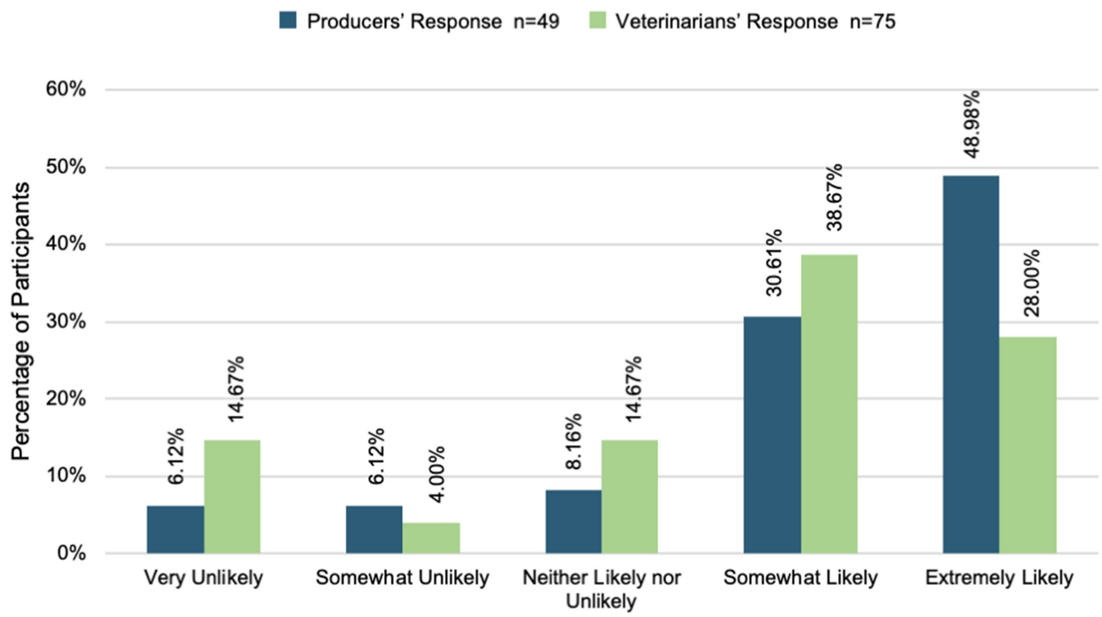

FIGURE 4
Willingness to partner to achieve goals.

3.1.5 Professional development training preferences

Veterinarians and producers also ranked preferences for continued education training and learning styles including length of time for in-person training. Both groups ranked "in-person learning communities" as most effective with a half-day time frame most preferred (22 and 41% respectively, Figure 8). Tables 1 and 2 describe training preferences.

3.2 Interview results

Upon survey completion, participants were invited to participate in a follow-up interview (Appendix B) conducted by a research team member. The responses were collected for analysis alongside the initial survey responses. Producers elaborated on barriers to sustaining operations, perspectives on existing relationships with veterinarians, and interest in pursuing and establishing a partnership with a

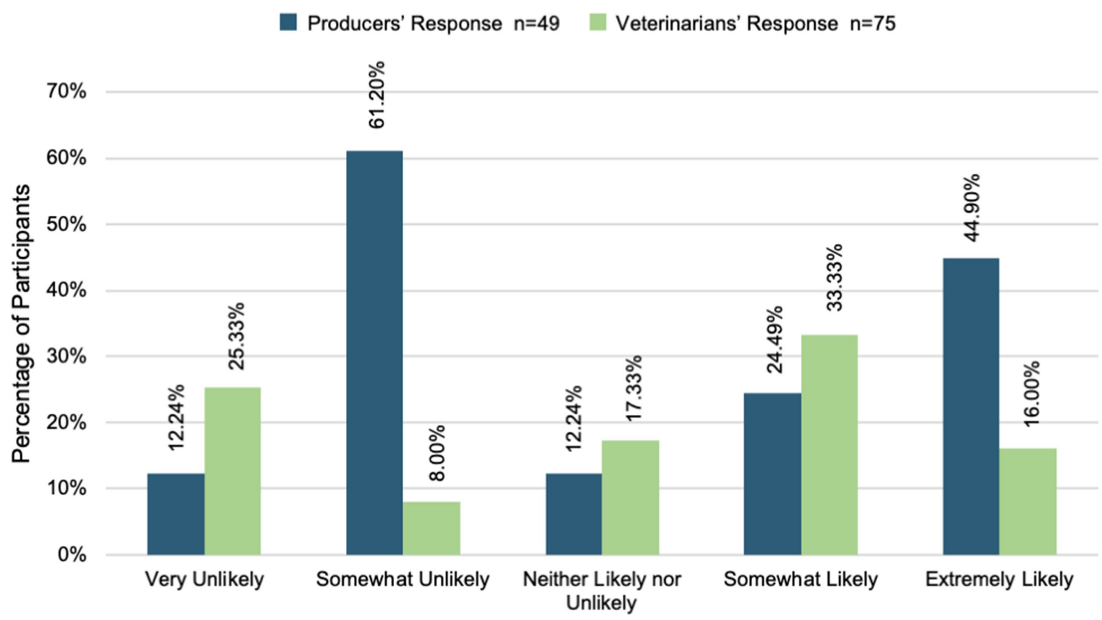

FIGURE 5
Willingness to partner to expand business.

veterinarian. Veterinarians who maintain a practice of less than 90% small animals were invited to participate in the follow-up interview. These veterinarians discussed the challenges faced in sustaining their practice, described relationships with producers, and offered perspectives on creating producer partnerships. Veterinarian and producer responses were analyzed separately for each type of data. The two sets of findings were compared to explore similarities and differences in perspectives and experiences. Both quantitative and qualitative findings for each group were integrated to arrive at study conclusions.

3.2.1 Veterinarian interviews qualitative findings

Fifteen veterinarians responded to 12 open-ended interview questions whereby they addressed thoughts regarding their practice, the type of care provided, perspectives on client-veterinarian relationships, and willingness to partner with producers. The twelve interview items produced a total of 531 coded passages which were further categorized into the following 10 themes. Within each theme, subthemes were identified (Appendix C). These themes, accompanied by respondent quotes, are presented below.

3.2.1.1 Theme 1: practice description

Respondents were asked to describe their current practice, including species seen. The responses revealed 12 subthemes regarding veterinarians' practice. These 12 subthemes were utilized 102 times when coding participant responses. Eleven out of fifteen veterinarians cited having a mixed animal practice, and only four practices were exclusively large animals. While all 15 veterinarians noted working with equine clients, over half of the participants also noted working with other species including bovine, swine, and small ruminants.

3.2.1.2 Theme 2: practice sustainability challenges

Veterinarians were asked about the challenges faced in maintaining and sustaining their practice. The theme of "Practice Sustainability Challenges," resulted in 55 coded passages with seven subthemes. Across the responses, veterinarians spoke to the growing challenges of sustaining their practices due to the cost of care, practice maintenance, and limitations of facilities lending to limited-service offerings. In 12 instances, interviewees spoke about the economics of veterinary medicine and the challenge of limited funds and resources. One participant stated, "Everyone wants to take the animals to the vet, but the cost–benefit is not there for food species… the horses and cats, it is still there but it is still an economic issue."

Many veterinarians noted that while they would prefer to be a solely large animal practice, however, veterinary medicine is not subsidized, and "the economics of what it costs (the practice) versus the value of the animal is often not compatible with producers seeking veterinary care." Thus, many veterinarians feel forced to turn to mixed animal practices to help make ends meet. "If I were strictly doing production medicine, then that would be wonderful. But no one can do that and make a living. So, I have to open my practice to dog and cat health now and that takes up time."

3.2.1.3 Theme 3: barriers to providing veterinary care

Veterinarians were asked questions related to how producers' provision of animal care has impacted their practice, as well as how relationships with producers influence their response to after-hours calls. Fifty-five coded passages highlighted the theme of barriers to providing veterinary care, and seven sub themes emerged. Of the 55 coded passages, statements relating to limited profit and time were the most abundant. For veterinarians, dependent upon an operation's size and care needed, they could see minimal financial gain in providing services. Additionally, many veterinarians held the perception that limited profit for the producer also presents a barrier to providing veterinary care. "In the producer's mindset, it is always a cost. This leads to resistance. There's an economic value in the animal that if your procedure exceeds that breakeven point, it is economically unproductive to do the procedure."

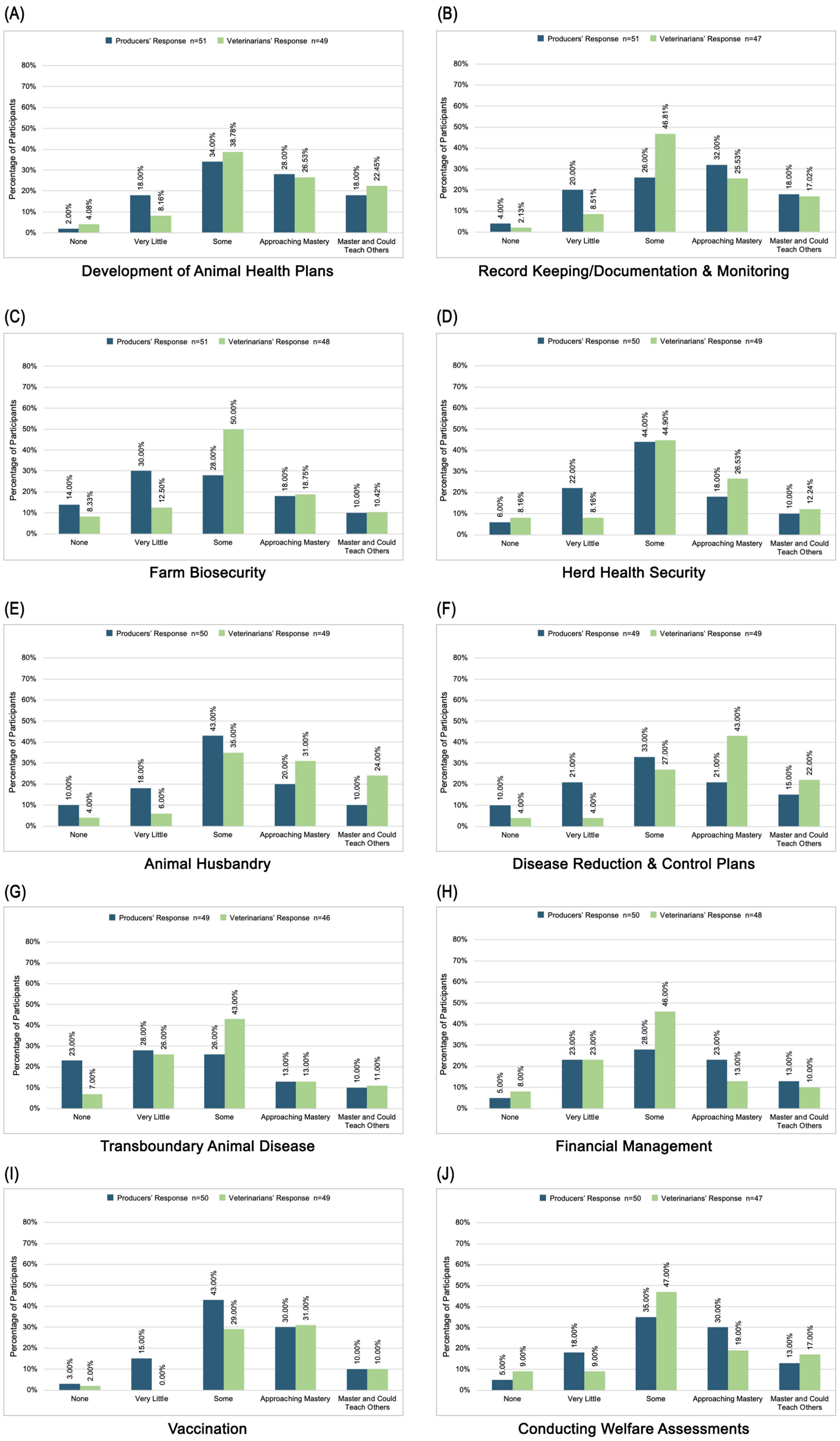

FIGURE 6
Self-assessment of knowledge in ten areas including **(a)** development of animal health plans, **(b)** record keeping/documentation and monitoring, **(c)** farm biosecurity, **(d)** herd health security, **(e)** animal husbandry, **(f)** disease reduction and control plans, **(g)** transboundary animal disease, **(h)** financial management, **(i)** vaccination, and **(j)** conducting welfare assessments.

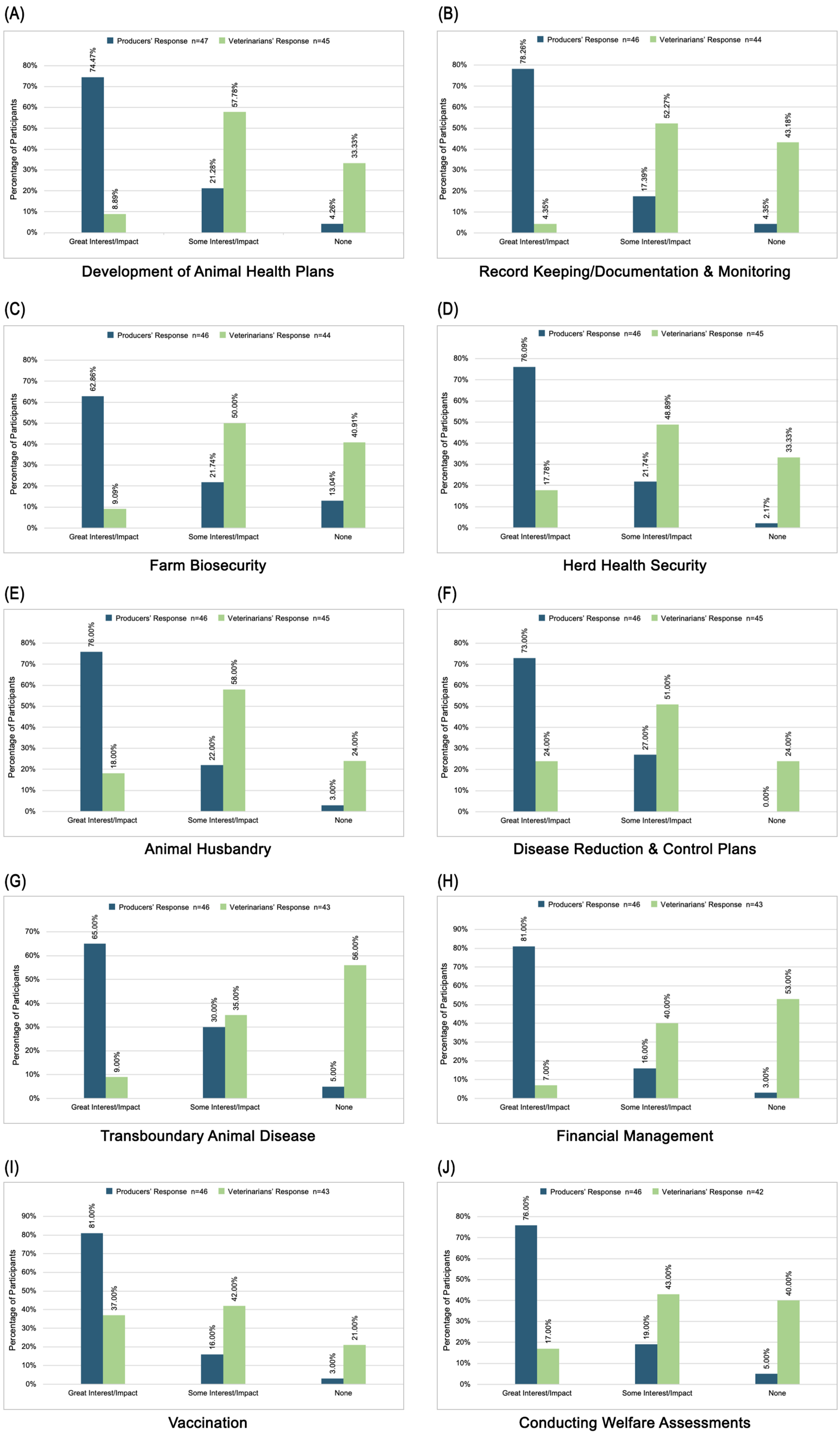

FIGURE 7
Impact of topic on developing a VCPR in ten areas including **(a)** development of animal health plans, **(b)** record keeping/documentation and monitoring, **(c)** farm biosecurity, **(d)** herd health security, **(e)** animal husbandry, (f) disease reduction and control plans, **(g)** transboundary animal disease, **(h)** financial management, **(i)** vaccination, and **(j)** conducting welfare assessments.

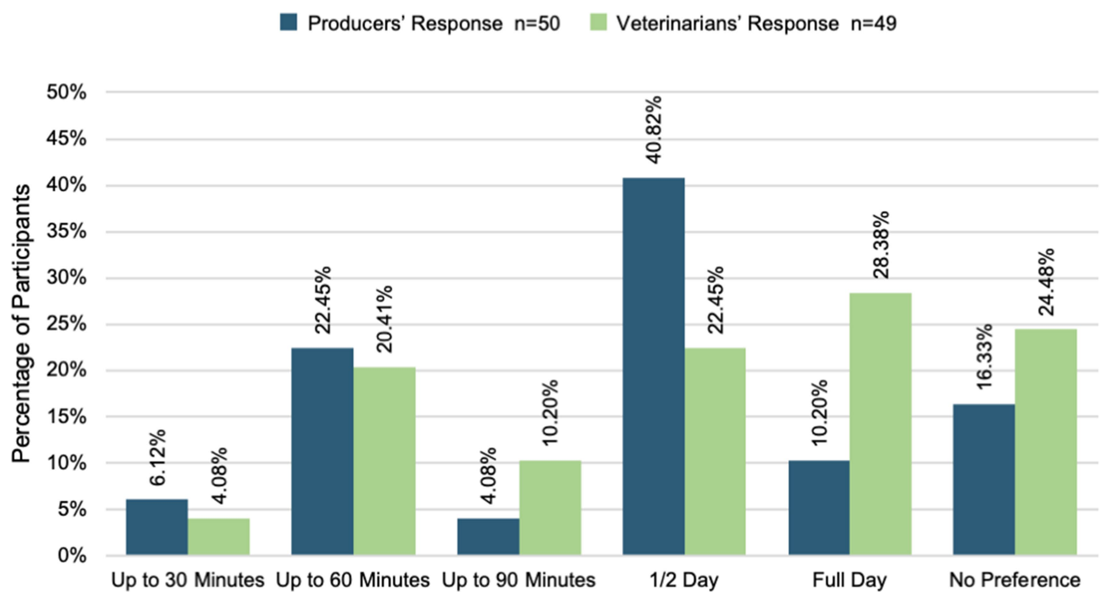

FIGURE 8
Preferred length of time for in-person training.

TABLE 1 Learning environment preferred by veterinarians.

Learning environment	Least effective	#	Somewhat effective	#	Most effective	#
Participating in an in-person learning community (e.g., monthly, or quarterly)	2.68%	3	9.22%	26	20.20%	20
Presentation(s) followed by discussion	1.79%	2	10.28%	29	18.18%	18
Workshops to address challenges	6.25%	7	9.57%	27	15.15%	15
Workshops to apply learning/complete an activity at session	5.36%	6	10.64%	30	13.13%	13
Online self-paced modules	15.18%	17	7.80%	22	10.10%	10
Informal discussions on designated topics	7.14%	8	11.35%	32	9.09%	9
Workshops to work on projects (e.g., group or individual)	11.61%	13	10.28%	29	6.06%	6
Online facilitated modules	14.29%	16	10.28%	29	4.04%	4
Online sessions using collaborative meeting software	19.64%	22	8.87%	25	2.02%	2
Participating in an online learning community (e.g., monthly, or quarterly)	16.07%	18	10.64%	30	1.01%	1

In addition to limited financial gain, time was also seen as a limiting factor. Five of the 15 respondents noted that they have placed boundaries around their time and mental health in an attempt to achieve work-life balance. For many, expectations to work after hours or on weekends is a strain on their family and so they have chosen to limit their availability. According to one veterinarian, "I will not provide services outside of my hours. We have enough demands on our time, our family, our mental and physical health."

Additionally, many veterinarians noted that 'not enough time' is a major challenge. Due to the high demand and limited availability of veterinarians, many producers have chosen to provide care themselves.

3.2.1.4 Theme 4: incentives to seeking veterinary care

Veterinarians were asked about incentives available for producers to engage with their veterinarian rather than handling herd health independently. The theme of Incentives to Seeking Veterinary Care resulted in 24 coded passages with four subthemes. Over half of the veterinarians interviewed spoke to the importance of producers having a veterinarian on record to request prescriptions. One stated, "Veterinary feed directive and prescription medications [are incentives]. We are obligated to have client and patient relationships, and some vets, sadly, do not follow that." Another shared, "You have to be careful as a vet and aware that people will call and want to get medicine and script for feed additive. If there is no relationship with a client and doctor, then I will have to say no to them." Several also noted that being on record often results in a smoother process for accessing needed care.

3.2.1.5 Theme 5: federal programs

Veterinarians were questioned about veterinary oversight in the form of federal programs like the Veterinary Feed Directive. Participants were asked how federal programs have influenced veterinary oversight in their practice. This line of inquiry served as

TABLE 2 Learning environment preferred by producers.

Learning Environment	Least effective	#	Somewhat effective	#	Most effective	#
Participating in an in-person learning community (e.g., monthly, or quarterly)	7.32%	3	24.39%	10	68.29%	28
Presentation(s) followed by discussion	16.67%	8	29.17%	14	54.17%	26
Workshops to address challenges	18.37%	9	32.65%	16	48.98%	24
Workshops to apply learning/complete an activity at session	2.50%	1	50%	20	47.50%	19
Online self-paced modules	16.67%	8	39.58%	19	43.75%	21
Informal discussions on designated topics	27.50%	11	37.50%	15	35%	14
Workshops to work on projects (e.g., group or individual)	15%	6	52.50%	21	32.50%	13
Online facilitated modules	25%	10	42.50%	17	32.50%	13
Online sessions using collaborative meeting software	15.79%	6	52.63%	20	31.58%	12
Participating in an online learning community (e.g., monthly, or quarterly)	33.33%	13	35.90%	14	30.77%	12

the foundation for 28 coded passages, and seven subthemes. Eleven out of fifteen veterinarians stated that federal programs have not impacted their practice, while three noted a positive increase and one a negative impact. When asked how federal programs influenced their practice, one veterinarian noted, "No change. I do not know of anyone that is concerned with feeding medicated feed. I have not seen it. Barely been asked about it." Another veterinarian felt federal programs had a positive association, stating, "I think that the change in the veterinary feed directives is a very good thing. I understand that it can change some of the producer outcome[s], but I am adamantly in line with the antimicrobials. We have got to protect our antibiotics. This has not affected my practice." This same veterinarian was quick to note that federal programs have streamlined how producers obtain medicated feed and medicines. However, other veterinarians were open about the challenges that remain in enforcing these programs. "The Veterinary Feed Directive has not changed our relationship much. Those who used the medications before are still coming to us for the feed. Those that did not come to us in the past still do not come. We're close to the border so there are lots of unlicensed practices along the border, and the state does not have the teeth to stop it. Those that do not want to have the relationships with the vet can still skirt the system."

3.2.1.6 Theme 6: producer provided animal care

Veterinarians were asked how producer-provided livestock healthcare has impacted their practice, animal well-being, and animal health. These questions resulted in 50 codes across eight subthemes. When questioned about how producer-provided livestock health care has affected their practice, nine out of fifteen shared that this had, "Economically, no effect at all. It does not affect me." However, several expressed some frustration in noting that producers have varied knowledge and skill sets when it comes to taking care of their animals. This results in producers contacting veterinarians only in emergencies. One veterinarian noted, "Smaller mom-and-pop producers seem to only reach out to veterinarians during emergencies."

Regarding the lack of veterinary oversight impacting animal well-being, over half of respondents felt that there was no impact, with one respondent expressing a negative impact. Similar to their feelings regarding the effect of producer-driven care on their practice, a majority of veterinarians expressed their main concern being producers' varied levels of knowledge and skills. "I think a lot of it is lack of education even in some very educated people…Some of the animal welfare issues we see are not from an intentional standpoint but there is just a lack of education…I do not have a problem with people doing some things, but at the same time there needs to be that level of education and that level of cooperation between a producer and veterinarian."

3.2.1.7 Theme 7: strategies to mitigate impact of producer-provided animal care on practice

Interviewees were asked to describe strategies that they have used to mitigate loss associated with producers providing their own animal care. Responses to this question led to 48 coded passages and four subthemes. Many veterinarians in early questioning expressed that little impact was felt by their practice; although, several shared strategies that they feel could result in a positive impact. Twenty coded passages focused on the value and importance of veterinarians providing timely responses and quality service. With time being a recognized barrier to the provision and seeking of care, many noted the importance of finding a better balance with their time to meet the needs of their clients. One veterinarian noted, "Give them better service. Answer the phone when clients call. The biggest complaint is producers cannot get the vets to call them back or come to visit their farm/ranch in a reasonable time period."

Participants also noted the importance of communication as the foundation of any relationship ultimately becoming the catalyst for developing new and improving existing relationships. Finally, 17 coded passages noted the importance of providing client education. "I think there needs to be a fair amount of education pushed. We need to have one-on-one conversations with these producers to let them know what we can provide different from others." Another veterinarian stated, "I try to be more informative with my clients and educate them on best care practices and why we need veterinarians instead of asking the internet for help." In addition to educating clients on the importance of veterinarians, some also noted that educating clients on procedures they can perform safely on their own, could promote partnerships with producers and set them up for success.

3.2.1.8 Theme 8: partnerships with producers

Veterinarians were asked if they would be willing to partner with producers to enhance their veterinary practice. Additionally, they were asked to describe what a partnership with a producer would look like. These two questions led to 48 coded passages and the development of seven subthemes, though one of the subthemes "no relationship—potential for delayed care," was utilized for responses to other interview items. All veterinarians interviewed shared their willingness to partner with producers. When asked what a partnership would look like, 10 participants shared that consistent communication would be key in establishing knowledge of a client's operation and needs. Additionally, six veterinarians expressed a desire to offer programming and education as part of the relationship, to ensure that they were supporting their clients in understanding best practices for care and overall herd health. For many veterinarians, partnerships form a community where clients are not just customers but friends as well. One veterinarian noted, "I live in a town with 1,300 people and about 5,000 in the county. The same people who are your clients are the people you hang out with, socialize with, and go to church with. There is a bond there."

While all veterinarians recognize that each producer partnership would be unique, they all expressed a desire to establish relationships built on mutual respect and a better understanding of one another.

In expanding on the topic of producer relationships, veterinarians were asked how established producer relationships impact your response to care outside of scheduled appointments or after-hours calls. Almost all veterinarians agreed (12 out of 15) that they would hesitate or choose not to see a client after hours unless there was an established relationship. While many want to help, they also want to maintain personal boundaries, especially when they have limited knowledge of a client's needs. One veterinarian stated, "I am much more able to help someone I have a working relationship with rather than an emergency relationship."

When describing relationships with producers outside of scheduled care, veterinarians reported various levels of relationships, with many noting that they are part of the same community as their clients. This leads to interactions outside of scheduled care that are most often noted as amiable or friendly. A respondent summarized the spectrum of responses when they stated, "It's no different than with people that are accountants or lawyers or teachers. Some are sociable friends, some are acquaintances, and some you never see outside your business."

3.2.1.9 Theme 9: methods for fostering/maintaining relationships with producers

Veterinarians were asked how they create and maintain producer relationships. Responses to these interview items resulted in 71 coded passages highlighting the theme. Through this theme, five subthemes emerged. Twelve out of fifteen veterinarians interviewed felt that building and maintaining trust is key to cultivating relationships with producers. One interviewee stated, "You have to partner with them, and you want your owners and producers to be as successful as they can be within their own limitations. I want to be on the asset side of the ledger, not the liability." Other respondents spoke to the importance of being authentic, treating producers with respect, and showing them how you can be of value to their operation. Nine veterinarians discussed the importance of increased collaboration, where 'it looks like a family relationship with two-sided equal and mutual respect.' When veterinarians and producers respect each other's roles within the relationship, it creates an environment conducive to collaboration and establishing shared goals for the operation.

In addition to trust and collaboration, veterinarians expressed that hosting seminars and training related to animal health and production could serve as gateways to establishing and maintaining producer relationships. By offering educational opportunities to grow knowledge and skills, veterinarians can help educate producers in areas that are relevant to their operations.

3.2.1.10 Theme 10: limitations to relationship development with producers

Veterinarians were also asked what might limit them from developing producer relationships. This question resulted in 44 coded passages and the emergence of seven subthemes. Every veterinarian expressed at least one limitation related to the lack of time for relationship development. Many recognize how limited their time is already, not including the additional efforts needed to establish and develop new relationships with producers. One veterinarian stated, "there is not enough time to get things done" while another shared that things could be different if they, "had more time, which would then allow for more availability." In addition to time, veterinarians also alluded to financial burdens and profit limitations that can come with creating producer relationships. One veterinarian noted sadly that, "It all revolves around money at the end of the day." While all veterinarians want to help, it is also understood that the size of the operation and the type of care being requested influence whether that work is profitable. Another participant noted, "Not sure about food animals, but the value of that animal has not kept up with the need to charge what we need to charge in order to make a living with the service…I have to charge what my time and energies are worth these days to make it worth it and not get taken out of the market."

The next section addresses the producer population and their interview responses.

3.2.2 Producer interviews qualitative findings

Twenty-two producers responded to 12 open-ended interview questions wherein they expressed views related to their operation, species of animals cared for, perspectives on veterinarian relationships, and willingness to partner with veterinarians. The 12 interview items produced a total of 407 coded passages which were further categorized into the following nine themes. Within each theme, subthemes were identified (Appendix D). These themes, accompanied by respondent quotes, are presented below.

3.2.2.1 Theme 1: operation description

Producers were asked to describe their current operation, including what species they raise. Through the responses provided, 10 subthemes emerged. These 10 subthemes were utilized 52 times when coding participant responses. Eight out of twenty-two producers cited having a small operation, with all but three producers raising bovine as part of their operation. In addition to raising bovine, participants also noted raising equine, swine, poultry, and small ruminants, with equine being the second most popular. A few producers also noted that they are Next Generation producers eager to carry on their family legacy.

3.2.2.2 Theme 2: operation sustainability challenges

Producers were asked about the challenges they face to maintain and sustain their operations. The theme of "Operation Sustainability Challenges," resulted in 62 coded passages with five subthemes. Across all responses, producers spoke to the growing challenge of sustaining their operations and herds due to the exponential increases in the cost of care and overall cost of the operation. In thirty-one instances, interviewees spoke to rising overhead costs for their operations and the resources needed to care for their animals. With limited funds and resources, many producers are finding it challenging to acquire and maintain the equipment and facilities needed, while also providing appropriate animal nutrition. One participant stated, "Challenges are high with infrastructure cost and equipment, high fertilizer cost, and wild hog damage to the pasture."

In addition to the cost of care, one producer noted that it was challenging for them to find a veterinarian to work with their swine, "There is not a veterinarian in the area that specializes in pigs. Everybody kind of does it because they have to. It's hard to find someone who knows about pigs and is willing to actually work with them."

Another producer spoke about lacking reliable transportation to get animal care should they need it. While noted less, some producers also mentioned difficulties due to pests, like wild hogs, and harsh weather. These producers spoke at length about the challenges they are facing with the current drought and having to decide to reduce herd size due to a lack of hay.

3.2.2.3 Theme 3: barriers to seeking veterinary care

Producers were asked why they choose to provide their own care instead of consulting their veterinarian, as well as how their relationship with a veterinarian influences responses to calls for after-hours care. Fifty-eight coded passages highlighted this theme, and 10 subthemes emerged. Of the coded passages depicting why producers often choose to provide their own care, statements relating to financial burden and preference for providing one's own animal care were the most abundant. For eighteen out of twenty-two producers, the financial burden brought on by the cost of veterinary care lends to the overwhelming preference to provide their own animal care when possible. One producer stated, "I do have a veterinarian provide the service sometimes, but I provide this care because of financial reasons. They [cattle] cost $50–$100 per head, and by the time you pay the chute fee and vaccination cost, it's at least $150 per head per cattle at that point."

Other producers noted time as a significant barrier. Producers often find it challenging to connect with veterinarians, or the time and distance associated with transporting the animal to receive care is not sustainable. "It's easier when it comes to scheduling, and it's cheaper. I like to do things by myself. I'm already home."

In this absence of a standing veterinary relationship, producers were asked to describe the impact on after-hours/emergency response. Two of the interviewees spoke about the potential for delayed care if they are not on file with a veterinarian. "If you wait until the middle of an emergency, it's too late to find somebody to help you…If you have to develop that relationship during an emergency, more than likely you will not survive the emergency." Another shared that in times of an emergency, they will "usually try to call a vet, and if no response I'll handle [it] on my own."

3.2.2.4 Theme 4: incentives to seeking veterinary care

Producers were asked about the benefits provided by veterinary involvement, as well as incentives available for engaging with their veterinarian. The theme of Incentives to Seeking Veterinary Care resulted in 44 coded passages with five subthemes. Over half of the producers ($n = 15$) interviewed shared that they were not aware of any incentives available for them to engage with their veterinarians. All 15 simply responded, 'No.' When asked about the benefits of veterinary involvement, 11 expressed the advantage of having veterinarians consult on their operation and overall herd health. One stated, "Primarily consulting. Like for illnesses, especially on the pigs. If one is showing signs of an illness, then being able to call and text a veterinarian for guidance is very beneficial."

Another shared, "You can call them, and sometimes, for instance, I had a cow have a fungus on his head, and I took a picture and sent it to the vet so we could talk about it over the phone." Several also noted that veterinary involvement provides them with access to more knowledge, on-site care, and assistance in securing prescription feeds or medications when a veterinarian is on record.

3.2.2.5 Theme 5: federal programs

Producers were questioned about the regulation of veterinary oversight in the form of federal programs like the Veterinary Feed Directive (VFD). Participants were asked how federal programs have impacted their livestock operations. This line of inquiry served as the foundation for 15 coded passages and one subtheme. Fifteen out of twenty-two producers stated that federal programs have not impacted their operations. They have an established record with the vet to obtain medicated feed or prescriptions when needed. The seven remaining producers chose to not answer this question. One nutritionist/producer noted that many veterinarians are not truly knowledgeable of programs like the Veterinary Feed Directive, creating conflict when questions arise. "As a nutritionist though, there have been some challenges. The biggest challenge is veterinarians do not understand the feed law. They are not 'educated' in the proper way of writing a veterinary feed directive. When you have an issue, veterinarians are very busy and it's hard to get them to focus on questions and issues you have with a VFD."

3.2.2.6 Theme 6: producer provided animal care

Producers were asked about their experience with providing their own animal care including what type of care they provide. Twenty-two coded passages highlighted this theme, and four subthemes emerged. All twenty-two producers shared that they provide some form of their own animal care, whether pest management (i.e., deworming), production management (i.e., castration, etc.) or vaccinations. One producer shared that providing this form of care was in their blood, as these skills have been passed down from previous generations and a veterinarian is not needed. When asked to describe their experience with providing their own care, 14 producers noted that providing their own animal care is easy and sustainable. One producer stated, "Most of the time, it's pretty easy" while another stated, "Self-service is the best." Meanwhile, five producers did note that providing care has its challenging moments and they will turn to their veterinarian in times of emergency. A participant confessed, "It can be challenging and tough doing it yourself."

3.2.2.7 Theme 7: partnerships with veterinarians

Producers were asked to describe the veterinary relationship outside of scheduled care; willingness to partner with a veterinarian to enhance your livestock operation; and what a veterinary partnership looks like. These three questions led to 57 coded passages and the development of nine subthemes. All producers interviewed minus one stated a willingness to partner with veterinarians to advance their livestock operation. When asked what a partnership would look like, 16 participants commented that consistent communication would be key to developing a relationship with a veterinarian such that they could become knowledgeable of their operation and overall herd. Many producers recognize that a veterinary relationship can give them greater insight into their herds' needs. For many producers, they also stress the importance of creating a relationship built upon mutual respect. One producer noted, "I think that it's important for the veterinarian to be priced fairly and for the producer to pay his bill promptly and not expect anything for free. There should be mutual respect between the two. Respecting [the] time of both people."

Like the quote above, six producers expressed wanting to have a partnership where the veterinarians provide necessary care and they in turn value the cost of that veterinarian's time and services. When asked about their relationship with their veterinarian outside of general scheduled care, three producers noted having no relationship, and 13 producers had a limited relationship outside of care. Four producers expanded further stating that the veterinarians are a part of their community. One producer noted, "It's a really good relationship because we get to communicate and get to see them at almost all gatherings."

3.2.2.8 Theme 8: methods for fostering/maintaining relationships with veterinarians

Responses to interview questions related to creating and maintaining veterinarian relationships resulted in 27 coded passages highlighting the theme. Through this theme, five subthemes emerged. To foster relationships, six producers pointed to consistent scheduled care as a means to establish a working relationship with the veterinarian. From there, three noted it is up to both veterinarians and producers to keep communication flowing. Twelve producers discussed the importance of increased collaboration, where the partnership results in 'trusting the person who will help take care of my animals.' In addition to collaboration and communication, producers expressed the value of educational opportunities to improve their knowledge and skills. One producer stated, "It would be nice to be available and have semi-annual or annual meetings between veterinarians and producers." These gatherings would promote education about regional animal health issues and aid producers in knowing when veterinarian involvement may be necessary.

3.2.2.9 Theme 9: limitations to relationship development with veterinarians

Producers were also asked to describe the limitations of developing veterinary relationships. This question resulted in 26 coded passages and the emergence of one subtheme. Every producer noted "time" as the primary limitation to nurturing a relationship with their veterinarian, whether their time constraints or the perceived time constraints of their veterinarian. One producer stated, "The hardest thing is just how busy veterinarians are. There is a huge demand for large animal veterinarians, and the more knowledgeable they are, the more busy they are. Being able to get that time, especially when dealing with pigs, he [the veterinarian] tries to fit him in when he can between horse clients. That is a challenge. Regardless of what they do, every veterinarian I've talked to is just busy with helping their other clients." Another producer reflected on their capacity for relationship development and noted that while they are interested in advancing their operation, they are, "Not available to do so."

4 Discussion of key findings

Data analysis resulted in multiple findings related to veterinarians' and producers' perspectives on the value of relationships and the overall impact on animal health. The analysis of quantitative findings supports the analysis of qualitative findings for both populations. In addition, the responses provided by both veterinarians and producers were similar. The coded passages across both populations were grouped into the following 10 main themes: (a) practice/operation description, (b) practice/operation sustainability challenges, (c) barriers to seeking/providing veterinary care, (d) incentives to seeking veterinary care, (e) federal programs, (f) producer provided animal care, (g) strategies to mitigate impact of producer provided animal care on operation (unique to veterinarians), (h) partnerships with veterinarians/producers, (i) methods for fostering/maintaining relationships with veterinarians/producers, and (j) limitations to relationship development with veterinarians/producers. Within each of these themes, more descriptive subthemes were identified. The majority of veterinarians and producers share similar perspectives and opinions regarding the value of veterinarian-producer partnerships, key relationship characteristics, and limitations to relationship development. The findings presented represent the collective view of both populations and the 10 main themes aggregated into five main ideas.

4.1 Time as a barrier

Responses provided by both veterinarians and producers indicate time as a significant barrier to relationship development and maintenance. Veterinarians and producers both recognize that veterinarians navigate heavy caseloads that often exceed standard workday hours. This results in limited time available to meet producers' needs and expectations. While fostering relationships results in additional clients, it also increases workload, leaving less time for themselves, their family, and their existing practice. Veterinarians view their lack of time as a key reason for not fostering and maintaining relationships with producers. This is supported by the overall lower percentage of veterinarians willing to partner with producers in areas of healthcare (72% versus 90%), goal achievement (67% versus 80%), and business expansion (49% versus 70%). Producers also find that time is a significant barrier to both relationship development and receiving animal care. Many producers are aware of veterinarians' busy schedules, yet frustrated that animal care is often not available in a timely manner. Whether it is the time required for a veterinarian to make a farm call, or the time required to transport an animal to the clinic, time constraints have become a key frustration and barrier to relationship development. Both veterinarians and producers recognize that time will remain a barrier and see limited solutions to combat this challenge.

4.2 Business as a profit or burden

Across all interviews, the financial challenges associated with running a veterinary practice or a livestock operation were discussed.

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Every veterinarian addressed the financial burden and responsibility of caring for animals. Several veterinarians also spoke to the limited profit found in their practice. They described the burden of paying off debts while simultaneously charging reasonable fees to balance affordability with profitability. Many veterinarians have found limited profit in operating exclusively large animal practices. In fact, veterinarians' willingness to partner with producers to grow their business rated lowest at 49% of all partnership willingness areas. Both veterinarians and producers feel the pressure of maintaining their operations/practices amid rising overhead and animal care costs. Veterinarians also recognize the challenge that producers face when making decisions related to animal care, as they too must make economic decisions when determining the types of services offered. For example, they must operate mixed animal practices, even if they prefer to practice exclusively on large animals, to ensure their financial stability. However, many veterinarians interviewed held the perspective that producers will not seek veterinary care if they believe the expense outweighs the animal's market value. Veterinarians note financial decisions as the reason many producers provide their own animal care, regardless of whether they have the knowledge and skills to do so. As such, veterinarians perceive that producers negatively view their services, except in the case of emergencies, because regular veterinary involvement limits profit. Quantitative evidence does not support this perception as almost half, 48%, of producers seek veterinarian input for animal health questions and more than 60% expressed interest in animal health continuing education topics. Every producer stated that their animals are their livelihood. Therefore, if the cost of veterinary care is unaffordable, they will provide their own care and redistribute those funds into other parts of the operation. Although producers desire veterinary assistance whenever their animals need care, they lack the financial security to always obtain it in a traditional manner. They would like support from their veterinarian, in the form of education and training, to provide some services on their own. This would allow them to use funds conservatively; improving the business sustainability of their operation.

4.3 Communication is key

Veterinarians and producers agree that successful relationships are founded on clear and consistent communication. Their opinions differ regarding the medium through which communication happens. While many producers are interested in communicating across different mediums—social media, email, etc., veterinarians are more hesitant to pursue those forms of communication. The extremely low percentage (0–6.4%) of producers aware of veterinarians' full range of services demonstrates this hesitancy in embracing various communication outlets. Producers expressed interest in telemedicine as a solution to the barriers of time and distance. However, many veterinarians were disinterested in telemedicine preferring in-person care. Overall, veterinarians recognize communication as key to relationships, yet they feel challenged to be consistent communicators because of time constraints. The veterinarian's heavy workload limits their ability to connect with producers or respond promptly to their questions. This leads to the perception that they are unwilling to help. This challenge is coupled with some producers' expectations that veterinarians should have 24/7 availability. While producers understand the busy nature of veterinarians' work, there seems to be an underlying frustration that accessibility is not always possible. This lack of access and untimely communication has led some producers to believe their needs are not a priority. They feel they are better off providing care themselves because the delay in connecting with a veterinarian could adversely impact the animal's health and thus the producers' entire operation.

4.4 Competing perspectives

Review of producer and veterinarian feedback reveals a shared acceptance that barriers exist between these two groups, fueled by each believing a false narrative of the other. These misconceptions have resulted in relationships either built out of necessity or never built at all. Many veterinarians perceive that producers do not recognize the value of their services. Instead, they feel like a safety net for producers when care goes wrong. Further, they think that producers are strictly concerned with the cost of care as it compares to the animal's market value. When having to choose between providing care or making a profit, they always decide in favor of profitability. Alternatively, many producers feel that veterinarians are less willing to help due to their limited accessibility and divisive attitude regarding producers providing animal care. Several producers were candid in their responses about the difficulties in making hard financial decisions to ensure operation sustainability while providing necessary animal health care. Producers feel they should be supported in providing some forms of animal healthcare themselves. Overall, many producers feel that veterinarians do not respect the choices they make regarding their operations, resulting in limited trust and a hesitation to form partnerships. Despite these unfavorable perceptions, veterinarians and producers actually share much common ground. While facing similar challenges to ensuring the success of their businesses—expense, weather, and availability of care—they both recognize the importance (74% of producers) and impact (56% of veterinarians) of continuing education, and the majority (> 65%) are willing to develop partnerships.

4.5 Mutual respect

Across all interviews, producers and veterinarians expressed a desire to create partnerships founded on mutual respect for decisions surrounding each other's practices/operations. Producers respect veterinarians' expertise. Forty-eight percent seek animal health care information from their veterinarian. Therefore, veterinarians have some influence and responsibility in building relationships. Communicating clearly and empathetically about challenges and seeking insight, then actively listening, to factors determining producers' decisions may foster this respect.

5 Conclusion

Greater than 65% of participants indicated a desire to create partnerships for animal health and to achieve goals—a tacit acknowledgment by both parties of the importance of veterinarian/

producer relationships. Additionally, more than 60% of producers expressed a high level of interest in participating in continuing education. Veterinarians, concurrently, expressed a need for more animal health education among producers and believe this effort will positively impact the veterinarian-producer relationship. Both parties believe in-person learning communities are the most effective means to gain knowledge and skills. Based on this information, we propose that collaboratively led applied education programs possess significant potential for developing partnerships by addressing the barriers of communication, perspective, respect, profit, and time. In this learning environment, veterinarians and producers have a “place at the table” promoting communication, mutual respect, and opportunities to share perspectives on goals, motivations, and experiences. Qualitative interview data suggests that veterinarians and producers desire these relationship characteristics and believe such traits can improve their practices/operations. The profit barrier could also be addressed through education by utilizing data to demonstrate the realized cost–benefit of preventive versus reactive animal health management. Time remains a serious hurdle in implementing educational programs and developing veterinarian/producer partnerships. Additional studies are needed to determine how to influence veterinarians and producers to prioritize educational programs and partnerships. One solution could be enlisting the support of extension programs, veterinary schools, and professional organizations to promote, incentivize, and implement these programs. Veterinarian and producer partnerships are the cornerstone of sustainable and profitable rural practices and small to medium-sized livestock operations. Collaborative education programs can provide the framework to remove existing partnership barriers and build a foundation for these relationships to grow and evolve.

Data availability statement

The datasets presented in this study can be found in online repositories. The names of the repository/repositories and accession number(s) can be found at: https://hdl.handle.net/1969.1/203139

Ethics statement

The studies involving humans were approved by Texas A&M University Institutional Review Board IRB2021-0582M. The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study.

Author contributions

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

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The author(s) declare that no Gen AI was used in the creation of this manuscript.

Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fvets.2025.1521440/full#supplementary-material

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Simplified climate change adaptation strategies for livestock development in low-and middle-income countries

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Climate change, characterized by the increased frequency and intensity of extreme weather events, is the greatest environmental challenge threatening global food systems. Its impacts are particularly severe for livestock production systems in developing countries. In low-and middle-income countries (LMICs), livestock production provides critical livelihoods for millions of vulnerable people and plays a significant role in food security. However, the sector is highly susceptible to the adverse effects of climate change. Climate change in LMICs is associated with erratic rainfall, rising temperatures, flooding, drought, desertification, and a higher frequency of extreme weather events. In particular, when temperatures exceed the thresholds projected by the Intergovernmental Panel on Climate Change (IPCC), livestock are subjected to heat stress, which reduces productivity, lowers conception rates, and can be life-threatening for many species. In response, various climate adaptation strategies have been implemented to enhance resilience in livestock production systems. This review evaluates existing adaptation strategies including their effectiveness in LMICs and proposes simplified and targeted adaptation strategies to build resilience in livestock production systems. Key adaptation measures include genetic improvement and diversification of livestock species, early warning systems, precision livestock farming technologies, climate-smart strategies, institutional and policy frameworks and capacity-building initiatives. Further, key factors influencing adaptation strategies outcomes such as governance, financial investment, community engagement, and technological infrastructure were highlighted. While some strategies such as breeding programs for heat-tolerant livestock and early warning systems have yielded positive results, challenges including limited financial resources, weak institutional frameworks, and resistance to change hinder their widespread adoption. The review also provides recommendations for improving adaptation strategies, including enhanced investment in data-enabled innovations, integration of climate adaptation policies into national development plans, and increased participatory approaches involving local livestock farmers. In conclusion, this study provides a roadmap for building climate-resilient livestock production systems in LMICs to ensure sustainable food production and improved livelihoods under changing climate.

KEYWORDS

climate change, livestock production, adaptation strategies, resilience, food security, indigenous breeds, precision livestock farming

1 Introduction

According to FAO (2006) and the World Bank (2020), the global livestock sector contributes 40% of the world's agricultural gross domestic product, employing one to three billion people and providing a livelihood base for about one billion individuals living in poverty. Livestock serves as a critical resource for low-income populations, including pastoralists who rely entirely on livestock, agro-pastoralists who raise crops and livestock, and smallholder farmers who primarily depend on crops but also keep livestock. These groups represent key players in complex and interconnected livestock value chains globally. Further, livestock products are also vital to global food security, contributing 17% of global kilocalorie consumption and 33% of global protein consumption (Rosegrant et al., 2009; Godde et al., 2021; Erdaw, 2023). Despite its substantial contribution to global economic development as highlighted, the livestock sector faces numerous challenges, with climate change being one of the most significant (Rojas-Downing et al., 2017; Cheng et al., 2022). Climate change is characterized by the increased frequency and intensity of extreme weather events, representing the greatest environmental challenge and a global threat to food systems especially in low and middle-income countries (LMICs). LMICs, as of 2024, are classified by the World Bank as nations with a gross national income (GNI) per capita of $4,465 or less (World Bank, 2024). These countries are primarily located in Africa, Asia, Latin America, and parts of the Pacific. They are disproportionately affected by climate change due to high dependence on climate-sensitive sectors, such as agriculture and livestock farming. They are also characterized by limited financial and technological resources to implement large-scale adaptation measures to climate change.

Extreme weather events such as droughts, rising temperatures, heat stress, unpredictable rainfall, and increased flooding are likely to adversely affect livestock production both in the short-term and long-term (Godde et al., 2021; Thornton and Gerber, 2010). For example, during the 2011–2012 period, Mexico experienced its most severe drought in 70 years, leading to substantial declines in livestock populations. Specifically, cattle and goat stocks decreased by approximately 3% across the country (Murray-Tortarolo and Jaramillo, 2019). Further, Mongolia's livestock industry has been recurrently affected by dzud—a climatic phenomenon characterized by harsh winters following dry summers. During the 2009–2010 Dzud crisis, approximately 9,000 families lost all their livestock, with an estimated 17% of the country's livestock perishing (Otani et al., 2015). Further, climate change poses a significant environmental threat not only to crops and animals but also to the entire human race (Thornton, 2010; Abbass et al., 2022). Its effects have serious implications for agriculture, livestock production, ecosystems, water resources, human health, soil quality, and the atmosphere. In many LMICs in the tropics and subtropics, the impacts of climate change are already evident. Weather-related disasters have become increasingly frequent over the past four decades, a trend that is predicted to deteriorate further (Thomas and López, 2015).

In terms of vulnerability, the agricultural sector, particularly the livestock sub-sector, is highly vulnerable to climate variability and extreme weather (Godde et al., 2021; Cervigini et al., 2013; Ayanlade et al., 2022). Depending on the region, climate change can manifest as fewer wet days, heavier rainfall, flooding, rising surface air temperatures, sea-level rise, and accelerated soil erosion. The Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (IPCC, 2007) identified many LMICs especially those in sub-Saharan Africa as being most vulnerable to climate change. Associated threats include food and nutrition insecurity, environmental degradation, and exacerbated poverty levels. The report further predicted that the frequency of extreme weather events will continue to aggravate their socio-economic conditions. Projections indicate that global average surface temperatures could rise by 1.8 to 4.0°C by 2,100—significantly higher than temperature increases observed in the last century. These challenges are expected to result in increased mortality and morbidity, further worsening poverty levels among millions of households. For instance, the Horn of Africa experienced an unprecedented multi-year drought from 2020 to 2023 which severely affected many livestock-dependent communities. In particular, the drought led to significant livestock deaths, with reports indicating that approximately 13.2 million livestock perished across Somalia, Ethiopia, and Kenya (Henchiri et al., 2024; Odongo et al., 2025). To mitigate the impacts of climate change on critical livelihood assets such as livestock, a variety of adaptation strategies must be implemented. This review presents a novel synthesis of climate change adaptation strategies specifically tailored for livestock production systems in low-and middle-income countries (LMICs). Unlike previous reviews that primarily discuss general adaptation measures, this study integrates emerging innovations such as precision livestock farming, data-enabled decision-making, and climate-smart genetic improvement programs. Additionally, it critically evaluates the effectiveness of existing strategies by incorporating recent case studies and empirical evidence from LMICs, an area that remains underexplored in climate adaptation literature. A key research gap addressed is the lack of region-specific, practical adaptation frameworks that consider the socio-economic and infrastructural constraints faced by livestock farmers in resource-limited settings. These strategies are intended for implementation by key stakeholders, including government agencies, non-governmental organizations (NGOs), livestock keepers, and other actors in the livestock sector, to mitigate the impacts of climate change on livestock productivity. In this narrative review, we synthesized existing knowledge on climate adaptation strategies for livestock production through qualitative comparison, with a focus on low-and middle-income countries (LMICs). Literature was selected from reputable databases, including Google Scholar, Scopus, Web of Science, and institutional reports from FAO, IPCC, and the World Bank. A thematic analysis approach was used to categorize adaptation strategies into key areas and key findings were presented in tabular format to facilitate structured analysis of adaptation measures, their benefits, challenges, and implementation feasibility.

2 Livestock production and climate change

Climate change can result from both natural and human (anthropogenic) influences (IPCC, 2013; Zheng et al., 2021). Among these, the production of greenhouse gases such as methane, carbon dioxide, water vapor, and nitrous oxide stands out as a major anthropogenic driver. According to IPCC (2013), the primary sources of these gases are the burning of fossil fuels and agricultural activities, including livestock production. The FAO (2006) report highlighted the significant role of the livestock production sector, identifying it as a major threat to environmental sustainability and biodiversity. The sector contributes up to 18% of anthropogenic greenhouse gas emissions—a figure reported to exceed emissions from the entire transport sector (Rojas-Downing et al., 2017). However, this claim has been disputed with estimates lower than this (Kristiansen et al., 2020; Twine, 2021; Scoones, 2022). Regardless of these debates, the livestock sector remains both a contributor to and a victim of climate change.

More than 60 billion land animals are reared and slaughtered annually for human consumption worldwide (FAO, 2020). Furthermore, livestock inventories are expected to double by 2050, with the majority of this growth occurring in developing countries (Steinfeld et al., 2006). As livestock numbers rise to meet increasing demand for meat, milk, and eggs, greenhouse gas emissions from the sector are likely to escalate, further exacerbating climate change and its adverse effects on livestock production, human health, and environmental sustainability. In addition to livestock production, other significant sources of greenhouse gas emissions include fossil fuel combustion, land use changes such as deforestation and desertification, and agricultural practices such as bush burning and fertilizer application (Rojas-Downing et al., 2017).

3 Impact of climate change on livestock production

Climate change has both direct and indirect impacts on livelihoods and livestock production systems in LMICs. Direct impacts include heat stress, flooding, and other extreme weather events that affect livestock assets and food systems (Godde et al., 2021). Indirect impacts extend to the economy, food security, and infrastructure. Valtorta (2009) highlighted four primary pathways through which climate change impacts animal production in tropical regions. Firstly, it reduces the availability of livestock feed-grains, leading to increased prices. Secondly, climate change causes declines in both the production and quality of pastures and forage crops, which are essential for livestock nutrition. Thirdly, it alters the distribution of livestock diseases and pests, potentially exposing animals to new threats. Lastly, extreme weather events directly affect animal health, growth, reproduction, and overall performance, further compounding the challenges faced by livestock producers. These impacts can result in significant adverse consequences for livestock production and yields, which in turn affect human livelihoods. Impaired performance and productivity, high mortality rates, and the loss of animals lead to reduced revenues, increased poverty, and hunger for individuals and communities. Rising global temperatures exacerbate these issues, especially for livestock production. Heat stress impairs livestock performance, reduces productivity, lowers conception rates, and can even be life-threatening (Thornton et al., 2022). Additionally, rising sea levels could flood pastures with saltwater, raising salinity levels and negatively affecting livestock feeds, fodders, forages, and grazing fields. Further, temperature changes may introduce vector-borne diseases, parasite infestations, and the transmission of diseases to new areas previously unaffected by these stressors (Thornton and Herrero, 2008). Addressing these challenges is critical to safeguarding livestock production and the livelihoods dependent on it. Detailed case studies of the impact of climate change on livestock production in LMICs are presented in Table 1.

4 Climate change adaptation strategies for the livestock sector development in LMICs

Adaptation to climate change, as defined by the IPCC (2001), involves adjustments in natural or human systems to actual or anticipated climatic stimuli and their effects, to mitigate harm or capitalize on beneficial opportunities. Adaptive capacity refers to a system's ability to adjust to climate change, including variability and extremes, to reduce potential damages, exploit opportunities, or cope with its consequences. The extent to which agricultural systems including the livestock sector are affected by climate change depends significantly on their adaptive capacity (Thornton and Herrero, 2008). Further, the impacts of climate change vary across regions, with some areas more severely affected than others. Climate change "hotspots" are regions where the effects are expected to be most pronounced. Using the Regional Climate Change Index (RCCI), Giorgi (2006) identified Sub-Saharan and Southern Equatorial Africa as primary hotspots in Africa. The RCCI evaluates regional responses to climate change by considering factors such as changes in mean precipitation, mean surface air temperature, and variability in these elements over time.

Africa's agricultural vulnerability to climate change largely stems from its reliance on rain-fed and underdeveloped farming systems. Most African farmers operate on a small scale, with limited financial resources, inadequate infrastructure, and inconsistent access to information (Thornton et al., 2009). Despite these challenges, the inherent diversity, context specificity, and traditional knowledge within African agricultural systems offer significant resilience to climate change (Thornton et al., 2014). Addressing the threats posed by climate change requires strategies to reduce vulnerabilities and enhance resilience. These adaptation strategies are essential for maintaining or improving livestock productivity in a rapidly changing climate (Herrero et al., 2008). These practices enable individuals and communities to cope with or adjust to climate change impacts (Nyong et al., 2007). In the livestock sector, adaptation measures focus on improving livestock tolerance to heat and their ability to thrive, grow, and reproduce under conditions of poor nutrition, parasites, and diseases exacerbated by climate change (Hoffman and Vogel, 2008). Such strategies are critical for ensuring food and livelihood security for livestock producers. Community-based interventions, like those documented by Oseni and Bebe (2010) in Kenya, have proven effective in building resilience among pastoral communities. Commonly adopted adaptation strategies include the use of emergency fodder during droughts, diversification of herd composition, improved breeding practices, de-stocking to manage heat stress, provision of shade, and supplementary feeding. These measures play a vital role in safeguarding the livelihoods of livestock-dependent communities in the face of evolving climatic conditions.

Adaptation strategies in livestock production systems can be categorized into different levels: herd, communal, national, and regional. At the herd level, strategies are tailored to small-scale livestock keepers and include measures such as documenting and selecting for heat-tolerant breeds, providing shade, and improving feed availability. At the communal level, collective approaches such as shared grazing

TABLE 1 Case studies on the impact of climate change on livestock production in low-and middle-income countries (LMICs).

Country/ Region	Climate change event	Direct impact on livestock	Indirect impact on livelihoods	Affected livestock system	Quantitative data	References
East Africa (Ethiopia, Kenya, Somalia)	Prolonged drought (2020–2023)	Significant livestock mortality due to starvation and dehydration	Increased food insecurity, loss of income, displacement of pastoral communities	Pastoral systems	Approximately 13.2 million livestock deaths across the region	Henchiri et al. (2024) and Odongo et al. (2025)
Sahel Region (Niger, Mali, Burkina Faso)	Recurrent droughts (2018–2022)	Reduced livestock productivity due to inadequate feed and water	Migration of pastoralists to urban areas, increased conflict over resources	Transhumant pastoralism	Decrease in herd sizes by up to 50% in some areas	Igbatayo et al. (2022) and Coly et al. (2023)
Bangladesh	Increased frequency of cyclones (2019–2021)	Livestock injuries and deaths, reduced milk production	Loss of assets, increased vulnerability to poverty	Small-scale dairy farming	Economic losses estimated at $1.5 billion in the agricultural sector	Rahman et al. (2023), Naim et al. (2023), and Islam (2025)
Andean Region (Peru, Bolivia)	Glacier melt and altered precipitation patterns (2015–2020)	Increased incidence of livestock diseases, reduced pasture availability	Decline in traditional livelihoods, food insecurity	High-altitude pastoralism	Reduction in alpaca populations by 30%	Pabón-Caicedo et al. (2020) and Liberman (2021)
Nigeria	Projected climate change impacts	Declining livestock productivity	Long-term GDP decline up to 4.5%, increased food imports, worsened food security	Mixed crop-livestock systems, pastoralism	Projected 20–30% reduction in crop yields long-term GDP decline of up to 4.5%.	Cervigini et al. (2013)
Mexico	Severe drought (2011–2012)	Decrease in cattle and goat populations	Income loss for livestock farmers, increased rural poverty	Extensive livestock farming	Approximately 3% decrease in cattle and goat stocks	Murray-Tortarolo and Jaramillo (2019) and Pérez and Jerez-Ramírez (2023)
Mongolia	Dzud (harsh winter following dry summer) (2009–2010)	Massive livestock mortality	Loss of livelihoods for nomadic herders, increased poverty	Nomadic pastoralism	Approximately 17% of the country's livestock perished; around 9,000 families lost all their livestock	Otani et al. (2015) and Rao et al. (2015)
Brazil (Amazon Region)	Deforestation linked to cattle ranching	Loss of biodiversity, soil degradation affecting livestock forage	Displacement of indigenous communities, conflicts over land use	Extensive cattle ranching	Significant increase in deforestation rates correlating with cattle ranching expansion	Alston et al. (2000) and Skidmore et al. (2021)
India (Rajasthan)	Heatwaves and water scarcity (2010–2015)	Heat stress reducing livestock productivity, increased disease incidence	Decline in household income, increased indebtedness among farmers	Smallholder dairy farming	Milk yield reductions of up to 15% during peak summer months	Ravindra et al. (2024) and Kulhari et al. (2024)
Peru (Andean Region)	Glacier retreat affecting water availability (2000–2010)	Reduced pasture availability leading to lower livestock productivity	Loss of traditional livelihoods, increased migration to urban areas	High-altitude pastoralism	Significant reduction in available grazing land due to shrinking glaciers	Chevallier et al. (2010) and Buytaert et al. (2017)

areas and community breeding programs are emphasized. At the national and regional levels, governments and organizations can implement policies and programs to support sustainable livestock practices and promote resilience to climate change. By employing these simplified strategies, livestock producers can build resilience, increase adaptive capacity, and reduce the impacts of climate change on livestock production systems. These efforts are crucial for ensuring sustainable livelihoods and food security in vulnerable regions. A detailed critical evaluation of these climate change adaptation strategies for livestock production including their benefits, challenges, implementation feasibility, cost implications, stakeholders involved, and scalability are presented in Table 2.

TABLE 2 Critical evaluation of climate change adaptation strategies for livestock production.

Adaptation strategy	Benefits	Challenges	Implementation feasibility	Cost implications	Stakeholders involved	Scalability
Resilience building and diversification of livestock species and breeds	Increases adaptability to climate stress, improves food security, enhances biodiversity	Resistance to change, need for extensive knowledge of suitable breeds, potential market limitations	High feasibility in mixed farming systems	Low to Medium - Costs involve acquiring diverse livestock species and farming systems, but can be offset by improved productivity and resilience	Livestock farmers, breeders, researchers, government agencies	High - Can be scaled across various agro-ecological zones and farm sizes
Early warning systems	Helps mitigate disaster impacts, reduces livestock losses, allows for timely interventions	Requires technological infrastructure, accessibility issues for rural farmers	Moderate feasibility in areas with good network coverage	Medium - Requires investment in meteorological data collection, communication infrastructure, and dissemination systems	Government agencies, meteorological departments, NGOs, local communities	High - Can be expanded to cover large geographic areas, but rural connectivity remains a limitation
Breeding strategies	Develops heat and disease-resistant livestock, enhances productivity and sustainability	Requires long-term investment, limited access to superior genetics in some regions	Moderate feasibility depending on genetic resource availability	Medium to High - Costs vary depending on whether traditional selection or advanced genomic approaches are used	Researchers, breeding organizations, government, farmers	Medium to High - Can be scaled with investments in breeding programs and farmer adoption
Application of science, technology, and innovation in building resilience and adaptation	Enhances efficiency, improves monitoring, and reduces resource wastage	High cost, limited technical expertise, potential lack of infrastructure in rural areas	Moderate to high feasibility with investment in R&D	High - Requires significant investment in research, infrastructure, and technology adoption	Universities, research institutions, private sector, government	High - Can be widely adopted but requires continuous investment in education and infrastructure
Capacity building for livestock keepers	Improves knowledge, enhances adoption of climate-smart practices, empowers local communities	Requires consistent training, potential resistance to new practices, language barriers	High feasibility with proper training programs	Medium - Costs include training materials, expert facilitation, and outreach programs	Government agencies, NGOs, universities, extension workers	High - Can be implemented in various communities with proper stakeholder involvement
Institutional policies for climate-smart livestock systems	Provides regulatory support, enhances sector-wide resilience, ensures long-term sustainability	Bureaucratic hurdles, policy inconsistency, limited enforcement capacity	Moderate to high feasibility with political will	Medium to High - Costs depend on policy development, implementation, and enforcement structures	Government, policymakers, international organizations	High - Policies can be adapted across national and regional levels
Precision livestock farming and data-enabled innovations for climate change adaptation	Real-time monitoring, data-driven decision-making, improves livestock management efficiency	High initial costs, requires technical knowledge, dependence on stable internet infrastructure	Moderate feasibility in rural areas, high feasibility in developed regions	High - Requires investment in IoT devices, software, and digital infrastructure	Private sector, research institutions, tech companies, large-scale farmers	Medium to High - More feasible for commercial farms but can be adapted for small-scale farmers with supportive policies

4.1 Short-term adaptation measures

Short-term adaptation measures are immediate, reactive interventions aimed at reducing the negative impacts of climate variability and extreme weather events on livestock production. These strategies are cost-effective, require minimal infrastructure investment, and are critical for preventing sudden losses in productivity and livestock mortality. The following short-term measures can help livestock farmers mitigate climate-induced stress and maintain productivity.

4.1.1 Resilience building and diversification of livestock species and breeds

To enhance resilience and mitigate the impacts of climate change, livestock farming systems in LMICs must adopt alternative options and strategic adjustments. One effective approach that could be adopted is the introduction of mixed farming systems, where farmers integrate crop and livestock production. Mixed farming systems often yield higher overall productivity due to complementary resource use (Sujatha and Bhat, 2015; Low and Meuwissen, 2023). Farmers also benefit from multiple income streams, which improve financial stability and food security. Furthermore, mixed species systems contribute to ecosystem health by maintaining ecological balance and enhancing biodiversity. Mixed farming also promotes nutrient cycling, as crop residues can be used as livestock feed, and livestock manure can enhance soil fertility. Additionally, providing shaded areas can reduce heat stress impacts on livestock, thereby improving their productivity and welfare. Moreover, enhancing livestock management through improved feeding regimes, effective disease control, and better reproductive management is essential for maintaining productivity under stressful conditions. Further, adjusting stocking rates helps prevent overgrazing by modifying the number of animals per unit area, ensuring sustainable pasture use. Implementing rotational grazing systems also allows pastures to recover, maintaining both the availability and quality of forage all-year. At the national level, coordinated guidelines for livestock production adjustments should be established. These standards should reflect the vulnerability and adaptive capacity of each community, ensuring that interventions are context-specific and sustainable. In addition, the development and implementation of climate-smart feed strategies are essential for enhancing feed efficiency and reducing greenhouse gas (GHG) emissions. These strategies include the use of specific feed additives and formulations. Additives such as tannins (Cardoso-Gutiérrez et al., 2021), seaweed extracts (McGurrin et al., 2023), and essential oils (Benetel et al., 2022; Jiménez-Ocampo et al., 2022) have been shown to mitigate methane emissions from ruminants. Precision feeding techniques also play a crucial role by optimizing nutrient intake, thereby reducing waste and environmental impact (Llorens et al., 2024). Additionally, utilizing locally available feed resources, such as crop residues and agro-industrial by-products, can decrease reliance on imported feed, lowering both costs and emissions. Effective manure management techniques through anaerobic digestion and compositing are also vital for reducing emissions and recycling nutrients (Chadwick et al., 2020; Dadrasnia et al., 2021). Anaerobic digestion captures methane from manure and convert it into biogas for energy production (Jameel et al., 2024). Composting, when properly managed, stabilizes nutrients, reduces methane emissions, and produces organic fertilizer. Biogas production systems not only help in emission reduction but also provide renewable energy for farm operations. Incorporating renewable energy into livestock farming systems could potentially reduce the carbon footprint. Solar-powered water pumps, for instance, offer a reliable water source for livestock in remote areas while reducing dependence on fossil fuels. Wind energy systems, through small-scale wind turbines, can power essential farm equipment, supporting sustainable operations. Additionally, bioenergy production from livestock manure and other organic waste helps reduce waste and provides clean, renewable energy.

Diversification of livestock species and breeds is an essential adaptation strategy to mitigate the impacts of climate change on livestock production systems. By keeping more than one species of livestock, farmers can generate a wider variety of livestock products and make better use of available forage in different seasons even in times of crisis. Diversification also mitigates risk by reducing the likelihood of total production failure, as species respond differently to climatic shocks. Examples of diversification practices include multi-species grazing systems, where cattle, sheep, and goats are integrated to optimize forage use and enhance productivity (Tohiran et al., 2023; Slayi and Jaja, 2024). Another practice involves integrating poultry farming with aquaculture, where chicken manure is used to enhance pond productivity (Njoku and Ejiogu, 1999; Shoko et al., 2019). A summary of proposed production adjustments in various livestock systems for climate change adaptation is presented in Table 3.

4.1.2 Early warning systems

Swift responses to perceived threats to livestock are crucial in building resilience and reducing their vulnerability (LEGS, 2014). Prompt interventions, such as relocating animals from affected areas during emergencies like floods and droughts, can significantly help in preserving key livestock assets. The specific intervention required depends on the nature of the emergency, the local context, and the phase of the emergency—whether it is ongoing, in the immediate aftermath, or during recovery or rehabilitation phases (FAO, 2016). The Livestock Emergency Guidelines and Standards (LEGS, 2014) offer comprehensive guidelines aimed at protecting and rebuilding the livestock assets of crisis-affected communities. These guidelines are designed with a focus on livelihoods objectives, providing rapid assistance to support communities in distress. LEGS is particularly valuable for a wide range of stakeholders, including donors, program managers, technical experts, NGOs, policy and decision-makers, educational institutions, and community-based organizations. It helps in identifying the most appropriate livestock interventions during disasters. Typical livestock interventions include the provision of animal health services, emergency feeding and water supplies, and shelter. Additionally, strategies such as destocking help manage livestock numbers during crises, while restocking efforts aim to rebuild herds post-crisis (FAO, 2016). It is crucial to prioritize adaptation efforts in communities where vulnerabilities are highest and the need for resilience is greatest. By focusing resources and efforts on these communities, interventions can be more effective in mitigating the impacts of emergencies and fostering long-term resilience.

4.2 Long-term adaptation measures

Long-term adaptation measures focus on sustainable, proactive strategies that enhance the resilience and productivity of livestock systems in the face of climate change. Unlike short-term interventions, these strategies require systematic planning, investment, and policy support but provide lasting benefits by reducing vulnerability, increasing efficiency, and ensuring food security. The key long-term adaptation measures include the following.

TABLE 3 Proposed production adjustments in various livestock systems for climate change adaptation.

Type of adjustment	Target livestock	Adjustment details	Objective	Possible outcomes/ Impact	Reference (s)
Rotational Grazing	Ruminant animals including cattle, sheep, and goats	Planned grazing schedules to allow pasture recovery and reduce overgrazing.	Ensure sustainable pasture use and reduce degradation.	Improved forage availability, increased livestock productivity, reduced soil erosion.	DeLonge and Basche (2017) and Henry et al. (2018)
Herd reduction	Pastoral livestock systems	Reduced herd sizes during prolonged droughts to match resource availability.	Minimize livestock mortality during resource scarcity.	Reduced herd losses, improved remaining livestock health and productivity.	Speranza (2010)
Shade provision	Ruminant animals	Constructed artificial shade structures and planted trees around grazing areas.	Mitigate heat stress in dairy cattle.	Increased milk yield, improved welfare, and reduced heat-related mortality.	Sullivan et al. (2011) and Masters et al. (2023)
Mixed farming systems	Smallholder farms (crops and goats)	Integrated goat farming with crop production; used crop residues as feed and manure as fertilizer.	Diversify income sources and optimize resource use.	Improved household income, enhanced soil fertility, and reduced feed costs.	Herrero et al. (2010), Thornton and Herrero (2014), and Thornton and Herrero (2015)
Intensive pasture management	Cattle	Introduced rotational grazing and reseeding of degraded pastures.	Enhance pasture productivity and mitigate overgrazing impacts.	Increased pasture biomass, improved livestock productivity, and carbon sequestration.	Rust (2018)
Agroforestry integration	Beef cattle	Incorporated trees into pasturelands to create silvopastoral systems.	Improve microclimates for livestock and enhance carbon storage.	Reduced heat stress, increased weight gain, and higher carbon sequestration rates.	Matocha et al. (2012) and Quandt et al. (2023)
Stocking rate adjustment	Sheep and goats grazing systems	Reduced stocking rates during drought to balance grazing pressure with pasture regrowth.	Prevent overgrazing and maintain pasture quality.	Improved pasture recovery and sustained livestock productivity.	Savian et al. (2021)
Renewable energy integration	Livestock farms	Installed solar panels to power ventilation and lighting systems in livestock houses.	Reduce reliance on fossil fuels and lower carbon footprint.	Lower energy costs, reduced GHG emissions, and improved energy efficiency.	Aroonsrimorakot et al. (2021)
Nutritional modification	Poultry	Inclusion of vitamin C and E in feed and water to ameliorate heat stress.	Enhance the antioxidant defense system to reduce oxidative stress caused by heat stress and improve physiological adaptation to high environmental temperatures.	Improved antioxidant status, better thermoregulation, improved performance, increased survival rates and economic benefits.	Abidin and Khatoon (2013) and Wasti et al. (2020)
Housing system change	Poultry	Transition from battery cages to enriched cage systems with perches, nesting boxes, and scratching areas.	Improve bird welfare and comply with animal welfare regulations.	Improved bird welfare, increased egg production quality, and consumer acceptance; potential for higher production costs.	Tactacan et al. (2009) and Renaudeau et al. (2012)
Alternative feed resources	Poultry	Use of insect-based protein (e.g., black soldier fly larvae) as a replacement for soybean meal in diets.	Reduce feed costs and dependency on conventional feed resources.	Improved sustainability, reduced feed costs, and comparable production performance to conventional feeds.	Khan (2018) and Belhadj-Slimen et al. (2023)

4.2.1 Breeding strategies

Breeding strategies play a pivotal role in enhancing the resilience and productivity of livestock under the increasing pressures of climate change. Significant differences in adaptation exist between livestock breeds and even within breeds, enabling targeted selection and improvement to meet specific environmental challenges. Indigenous livestock breeds are typically more adapted to changing climates (Ahlawat et al., 2015; Mathew and Mathew, 2023). They also have lower feed requirements and can efficiently utilize low-quality pasture and feeds (Ateş et al., 2014). Thus, identifying and strengthening local breeds that have adapted to local climatic stress and feed sources is key to breeding for resilience and adaptation to extreme climatic conditions (Rojas-Downing et al., 2017). For example, breeds such as the Red Maasai sheep (Radeny et al., 2022) and East African shorthorn zebu (Ayalew et al., 2023) demonstrate inherent resilience to harsh climates and diseases. These traits make them invaluable in breeding programs aimed at enhancing climate resilience. Breeding strategies that focus on resilience to heat stress and diseases are especially crucial to adapt to climate change. For example, the development of heat-tolerant cattle breeds, such as the Bonsmara in South Africa (Fedrigo et al., 2021), has shown success in improving resilience to high temperatures and disease resistance. Therefore, designing breeding programs that incorporate adaptation as a major breeding goal could potentially lead to progenies that are hardy, suitable, and well adapted to climate variability. Vulnerable stocks can also be improved through cross-breeding with more adapted breeds. At the herd level, breeding strategies could involve documenting and identifying stocks that have adapted to changing climates and whose performance and productivity are least affected by climate change impacts for breeding purposes. At the communal level, options for nucleus or community-based breeding programmes (CBBPs) should be explored. CBBPs have been utilized over the years under low-input systems in developing countries with considerable success for improving productivity and adaptation (Olaniyan et al., 2024). For instance, the productivity of the indigenous Djallonke sheep was improved in an open nucleus breeding scheme in Ivory Coast (Yapi-Gnaore et al., 1997a; Yapi-Gnaore et al., 1997b). Similarly, Abdel-Salam et al. (2010) reported high genetic gain in milk production of Egyptian Buffalo in open nucleus breeding scheme. Similarly, CBBPs for smallholder farmers in Liberia have resulted in genetic improvements for Liberian goats (Karnuah and Dunga, 2018). These models can be replicated in other regions to enhance climate resilience. Further, these showed that nucleus or community breeding schemes represent unique opportunities for genetic improvement of livestock at the communal level for adaptation to climate change impacts (Shrivastava et al., 2018). At the national and regional levels, investment and collaborative efforts are needed to design and implement breeding programs that incorporate adaptation as a major goal. Additionally, there should be investment in biodiversity conservation. Developing regional gene banks for animal genetic resource conservation can improve breeding programs and serve as an insurance policy against the erosion of valuable indigenous genetic resources. A summary of case studies of how indigenous livestock breeds could enhance resilience and adaptation to climate change is presented in Table 4.

4.2.2 Application of science, technology, and innovation in building resilience and adaptation

The Federal, State, and Local Governments in LMICs must make investments in scientific research and development for climate change adaptation. Advancing science and technology is a fundamental requirement for developing effective management strategies to cope with the anticipated impacts of climate change. Both basic and applied research in areas such as breeding and genetics, biotechnology, molecular biology, animal nutrition, pasture and range management, and animal health are essential. These fields will enhance our understanding of the expected impacts of climate change on livestock systems and help devise strategies to reduce their vulnerability. For instance, Oseni (2018) highlighted significant gaps in the application of science, technology, and innovations (STI) in the management of indigenous livestock resources across Eastern, Southern, and Western Africa through the EU-funded iLinova program. One notable area is the development of alternative livestock production systems, such as pasture-based systems, which reduce feed costs by incorporating natural supplements like insects and grasses (Sanusi and Oseni, 2020; Oseni and Bashiru, 2022). Additionally, the use of unconventional feedstuffs and kitchen waste as alternative feed sources has been shown to sustain livestock productivity without adverse effects. The program also emphasized the importance of regional collaboration for the institutionalization of STI in managing indigenous livestock. Such collaborations foster knowledge sharing, resource pooling, and the development of region-specific solutions to common challenges. By prioritizing research and innovation in these areas, a more resilient livestock sector that is better equipped to withstand the pressures of climate change could be attained in LMICs. This will not only protect livelihoods but also contribute to food security and sustainable agricultural development.

Government-led investments in science, technology, and innovation have been demonstrated as effective strategies for enhancing climate adaptation in LMICs. For example, in Bangladesh, the government has implemented the Bangladesh Climate Change Strategy and Action Plan (BCCSAP) to address the increasing threats of flooding and cyclones (Reid et al., 2012; Islam et al., 2013; Akon and Mia, 2024). Further, in Kenya, the Kenya Climate Smart Agriculture Strategy (KCSAS) promotes drought-resistant crop varieties and water-efficient irrigation technologies to mitigate erratic rainfall and prolonged droughts (Kenya Climate Smart Agriculture Strategy, 2025; Waaswa et al., 2024). In Ethiopia, the Sustainable Land Management Program (SLMP) has focused on soil and water conservation, reforestation, and agroforestry to combat land degradation and drought (World Bank, 2020; Schmidt and Tadesse, 2019). Detailed case studies of these investments including their impacts are presented in Table 5.

4.2.3 Capacity building for livestock keepers

There is an urgent need to enhance the capacity of livestock keepers and herders to understand and address the impacts of climate change on livestock production. Mobilizing various local and agrarian communities for climate change adaptation actions is critical to mitigating the adverse effects on key sectors and vulnerable populations. This mobilization should focus on implementing practical strategies and interventions that directly address the challenges posed by climate change. One crucial area for improvement is providing adequate training in heat stress management and fodder production. These skills are essential for ensuring a consistent supply of animal feed, which helps reduce malnutrition and mortality in herds. By equipping livestock producers with the knowledge and tools to manage heat stress and maintain fodder supplies, the resilience of livestock systems can be significantly improved. Strengthening the existing capacities of local authorities, civil society organizations, and the private sector is equally important. This capacity-building effort lays the groundwork for robust climate risk management and facilitates the rapid scaling up of adaptation measures through community-based risk reduction and effective local governance (Nyong et al., 2007). Enhancing these capacities ensures that communities are better prepared to respond to climate-related challenges and can implement sustainable adaptation strategies. For example, the Livestock and Climate Solutions Hub (ILRI, 2025) developed by the International Livestock Research Institute is a platform designed to support LMICs in transitioning to sustainable,

TABLE 4 Case studies of indigenous livestock breeds enhancing resilience and adaptation to climate change.

Country	Livestock breed	Specific traits	Key information	Reference(s)
Kenya	Red Maasai Sheep	Tolerance to endoparasites (e.g., gastrointestinal worms) Drought resistance	Used in crossbreeding programs to enhance parasite resistance in exotic sheep breeds.	Baker et al. (2003) and Baker et al. (2004)
Ethiopia	Boran Cattle	Heat tolerance - Disease resistance (e.g., tick-borne diseases) Efficient feed utilization	Boran cattle are integral to low-input systems and are being improved through selective breeding for milk and beef traits.	Haile et al. (2011) and Katiyatiya et al. (2017)
Nigeria	West African Dwarf Goat	Tolerance to trypanosomiasis Small size suitable for limited grazing areas	Central to smallholder farming systems for meat and milk production under low-resource settings.	Oseni et al. (2017)
Ivory Coast	Djallonke Sheep	Heat and humidity tolerance Resistance to gastrointestinal nematodes	Improved through an open nucleus breeding scheme to increase productivity without losing adaptability.	Yapi-Gnaore et al. (1997a) and Yapi-Gnaore et al. (1997b)
South Africa	Nguni Cattle	Tolerance to extreme temperatures Resistance to tick-borne diseases	Highly valued for extensive grazing systems and as a genetic resource for climate resilience.	Bayer et al. (2004), Mapiye et al. (2009), and Katiyatiya et al. (2017)
Zimbabwe	Mashona Cattle	Adaptation to semi-arid conditions Efficient use of poor-quality forage	Used in community breeding schemes to improve productivity and maintain adaptability traits.	Nyamushamba et al. (2016) and Tavirimirwa et al. (2019)
Liberia	Liberian Dwarf Goat	Heat tolerance Resistance to common local diseases	Improved productivity through community-based breeding programs (CBBPs).	Karnuah and Dunga (2018)
India	Gir Cattle	Heat tolerance High milk yield under tropical conditions	Gir cattle are extensively used in crossbreeding programs to develop high-yielding dairy breeds for tropical climates.	Patbandha et al. (2020) and Parikh et al. (2024)

climate-smart systems. This hub could potentially be used as a template to build and strengthen the capacity of stakeholders in livestock production in LMICs. The Hub aims to accelerate practical solutions to the challenges posed by climate change to livestock production. This initiative focuses on developing and scaling climate-smart livestock innovations, enhancing resilience and productivity, and guiding countries in meeting their climate goals under the Paris Agreement.

Exploring opportunities for grantsmanship in capacity building for climate change adaptation is another critical avenue. Grants from developed countries can play a significant role in not only building the human capacity necessary to address climate change impacts but also in fostering resilience, improving infrastructure, and raising the standard of living for livestock keepers. These grants can support training programs, infrastructure development, and the adoption of innovative practices that help communities adapt to the changing climate and safeguard their livelihoods.

4.2.4 Institutional policies for climate-smart livestock systems

Strengthening institutional and policy frameworks is critical for enhancing the adaptive capacity of the livestock sector in the face of climate change (USDA, 2013). Effective policies provide a structured approach to implementing adaptation strategies, fostering resilience, and ensuring long-term sustainability. Enacting favorable legislation, subsidies, grants, and insurance schemes can support livestock keepers in adopting climate-smart practices, mitigate financial risks, and secure their livelihoods. For example, in Malawi, the government has integrated Climate-Smart Agriculture (CSA) into national policies to enhance agricultural resilience (World Bank, 2025). This integration includes promoting sustainable land management practices and supporting livestock keepers in adopting climate-resilient strategies. However, in Uganda, efforts to implement climate change adaptation policies in the livestock sector have faced institutional challenges (Ampaire et al., 2017). This highlights the need for coherent policy frameworks and effective institutional coordination to support livestock keepers in adapting to climate change. A well-defined "Climate Change Adaptation Strategy for the Livestock Sector" should be developed to serve as a guiding framework for national, regional, and local governments, as well as research institutions and private stakeholders. This strategy should outline specific actions, allocate resources, and establish measurable goals to ensure effective implementation of climate adaptation initiatives. Integrating climate-smart principles into agricultural policies will not only support livestock resilience but also promote sustainable land use and resource conservation.

The Climate-Smart Agriculture (CSA) approach provides a comprehensive framework for adaptation and mitigation within the livestock sector (Lipper and Zilberman, 2017). By optimizing resource use and reducing greenhouse gas emissions, CSA strategies enhance productivity while minimizing environmental impact (Sekaran et al., 2021; Jalón et al., 2016). Key interventions include precision breeding for resilience, improving feed efficiency, and promoting integrated crop-livestock systems. The adoption of water-efficient irrigation methods, enhanced pasture management, and afforestation programs further contribute to sustainability. A critical component of

TABLE 5 Case studies on government investments in STI for climate adaptation in LMICs.

Country	Climate challenge	Government investment initiative	Science, technology, and innovation (STI) applied	Impact on resilience and adaptation	Quantitative data	Reference
Bangladesh	Frequent flooding and cyclones	Implementation of the Bangladesh Climate Change Strategy and Action Plan (BCCSAP)	Development of climate-resilient infrastructure, such as elevated roads and cyclone shelters	Enhanced community resilience to climate-induced disasters	Over 2,500 cyclone shelters constructed, serving approximately 5 million people	Reid et al. (2012), Islam et al. (2013), and Akon and Mia (2024)
Kenya	Drought and erratic rainfall affecting agriculture	Launch of the Kenya Climate Smart Agriculture Strategy (KCSAS)	Promotion of drought-resistant crop varieties and water-efficient irrigation technologies	Improved food security and farmer livelihoods	Adoption of climate-smart practices by over 600,000 farmers	Kenya Climate Smart Agriculture Strategy (2025) and Waaswa et al. (2024)
India	Water scarcity and heatwaves	National Initiative on Climate Resilient Agriculture (NICRA)	Development of heat-tolerant crop varieties and water-saving technologies	Increased agricultural productivity under climate stress conditions	Yield improvement of 15–20% in stress-prone areas	Venkateswarlu et al. (2013) and Singh et al. (2022)
Ethiopia	Land degradation and drought	Sustainable Land Management Program (SLMP)	Application of soil and water conservation techniques, reforestation, and agroforestry practices	Restoration of degraded lands and improved agricultural productivity	Rehabilitation of over 2 million hectares of land	World Bank (2020) and Schmidt and Tadesse (2019)
Vietnam	Sea-level rise and salinity intrusion	Mekong Delta Plan for Climate Resilience	Construction of salinity intrusion monitoring systems and development of salt-tolerant crop varieties	Protection of agricultural lands from salinity and maintenance of crop yields	Salinity intrusion reduced by 60% in targeted areas	Du et al. (2022) and Hills to Ocean (2023)
Rwanda	Soil erosion and irregular rainfall	Rwanda Climate Change and Low Carbon Development Strategy	Implementation of terracing, rainwater harvesting, and agroforestry	Enhanced soil fertility and water availability for agriculture	Soil erosion reduced by 50% in implemented areas	National Strategy on Climate Change and Low Carbon Development for Rwanda (2011)

climate-smart policies is the promotion of sustainable land management and biodiversity conservation. Encouraging agroforestry, rotational grazing, and pasture rehabilitation can help restore degraded lands, enhance carbon sequestration, and improve livestock productivity. Additionally, leveraging data-driven innovations, such as remote sensing and predictive modeling, will enable better decision-making in climate risk management. To ensure the successful implementation of climate-smart policies, multi-stakeholder collaboration is essential. Governments, research institutions, the private sector, and civil society organizations must work together to develop and enforce policies that support climate adaptation. Providing financial incentives for sustainable practices, investing in early warning systems for climate-related risks, and fostering regional cooperation will further strengthen resilience in the livestock sector. By embedding climate adaptation strategies within national policies and leveraging innovative agricultural practices, LMICs can build a more resilient livestock industry, ensuring food security and sustainable development amid evolving climate challenges.

4.2.5 Precision livestock farming and data-enabled innovations for climate change adaptation

The rapid advancements in technology offer unprecedented opportunities to transform livestock production and make it more adaptive and resilient to the impacts of climate change. Precision livestock farming (PLF), coupled with data-enabled innovations, provides tools to monitor, manage, and optimize livestock production systems in real-time. These innovations enhance decision-making, improve resource use efficiency, and mitigate the adverse effects of climate variability (Pardo et al., 2022; Papakonstantinou et al., 2024). One of the most promising developments in PLF is the deployment of Internet of Things (IoT)-enabled sensors, which are cost-effective and scalable for use in low-resource settings. These sensors provide continuous monitoring of key environmental and animal health parameters, enabling farmers to track temperature, humidity, and other climatic variables within livestock housing systems. For instance, early detection of heat stress conditions allows farmers to implement cooling measures such as misting or ventilation adjustments (Islam et al., 2021). Further, Oseni et al. (2025) utilized low-cost IoT sensors to monitor environmental parameters, such as temperature, humidity and noxious gases, for optimal health and welfare of broiler chickens raised under tropical conditions in Nigeria. In addition, wearable sensors on livestock can monitor physiological metrics such as heart rate, body temperature, and activity levels (Neethirajan, 2017; Alipio and Villena, 2023). These data help detect early signs of illness, or heat stress, enabling timely interventions. Furthermore, sensors can also be integrated into feed bins that can measure feed intake in real-time (Shelley et al., 2016; Gonzalez et al., 2018), allowing precise adjustments to meet nutritional requirements while minimizing waste and greenhouse gas emissions. IoT devices can also monitor water quality and consumption, ensuring that livestock have access to clean water, especially during periods of drought or extreme heat.

Data collected through IoT sensors are analyzed using advanced analytics and machine learning algorithms to provide actionable insights for farmers. Decision support systems (DSS) built on these platforms can be applied for weather forecasts (Ahmad and Hossain, 2019) and historical climate data integrated with livestock performance metrics can predict risks such as heatwaves or disease outbreaks (Bett et al., 2017) to help farmers plan preventive measures. In addition, DSS tools can recommend optimal stocking densities, grazing schedules, and rotational grazing practices based on real-time pasture conditions. Data on animal performance and genetic traits can also guide selective breeding efforts to develop heat- and disease-tolerant livestock. However, while PLF and IoT innovations hold great promise, challenges such as high initial costs, limited internet connectivity in rural areas, and low technical expertise among farmers must be addressed. Governments, NGOs, and private sector stakeholders should collaborate to provide subsidies and financial incentives for adopting PLF technologies, invest in infrastructure to improve internet access in rural areas and organize training programs to build farmers' capacity to use these technologies effectively. Furthermore, IoT-enabled systems can be powered by renewable energy sources, such as solar panels, to ensure sustainability in regions with limited access to electricity. For instance, solar-powered water pumps and ventilation systems can be automated based on sensor inputs, reducing dependency on fossil fuels while ensuring animal welfare.

5 Analysis of climate change adaptation strategies and challenges in their implementation

5.1 Comparative analysis of climate adaptation strategies in livestock production: key factors for success

Climate adaptation strategies in livestock production vary widely across regions, with differing degrees of success. These strategies are influenced by financial resources, community engagement, technical support, and environmental conditions. Therefore, analyzing these strategies provides valuable insights into the critical factors determining their effectiveness. A major determinant of success is technical and financial support. For example, silvopastoral systems (SPS) in Montería, Colombia, achieved success due to the integration of innovative grazing techniques, financial investment, and technical expertise, which enhanced pasture growth and improved carbon sequestration (Rivera et al., 2019; Chará et al., 2017). Similarly, breeding improvement programs in Northern Kenya benefited from structured training, favorable environmental conditions, and community participation, leading to increased productivity (Ojango et al., 2023). In contrast, adaptation strategies such as destocking during droughts in Namibia failed due to low herd sizes, unfavorable market conditions, and cultural barriers (Siririka et al., 2025). Another key factor is community engagement and acceptance. Disease management training in Northern Kenya was successful due to the active participation of pastoral communities and the integration of veterinary services, resulting in improved livestock health (Ojango et al., 2023). Conversely, climate-resilient livestock housing in Bangladesh failed due to high maintenance costs and low farmer adoption, leading to 40% of shelters being abandoned (Rahman, 2022). Institutional and policy support also plays a crucial role. Water management strategies in Namibia had mixed success, highlighting the need for stronger government support and financial assistance (Siririka et al., 2025). Similarly, climate change adaptation efforts in Northeastern Iran were hindered by regulatory weaknesses and inadequate insurance mechanisms, emphasizing the necessity of comprehensive policy frameworks (Sharafatmandrad et al., 2024). Finally, technology integration has shown promising results. Mobile climate advisory services in Uganda effectively reduced livestock losses and increased farm income through real-time weather and market information, facilitated by strong mobile network infrastructure and public-private partnerships (Tuheirwe-Mukasa et al., 2019). A detailed summary of these strategies and their effectiveness is presented in Table 6.

5.2 Challenges in implementing climate change adaptation strategies in LMICs

Several challenges hinder the effective implementation of climate change adaptation strategies. A primary challenge is limited financial resources which significantly impede the adoption of adaptation measures. Many LMICs struggle to allocate sufficient funds for climate initiatives due to competing development priorities. According to Nelson et al. (2016), high poverty levels and limited access to education in LMICs can reduce the capacity of communities to adopt new adaptation strategies. Limited research and development capacity in LMICs also restricts the generation of context-specific adaptation solutions (Obe et al., 2025). This knowledge gap hinders the development and implementation of effective strategies. Furthermore, as noted by Biesbroek et al. (2013), weak institutional frameworks and governance structures also obstruct the coordination and execution of adaptation policies in LMICs. Challenges such as bureaucratic inefficiencies and lack of clear mandates often lead to ineffective adaptation efforts. In addition, inadequate integration of climate adaptation into national policies and development plans can result in fragmented efforts (Lee et al., 2022). Limited access to technology and technical expertise required for some strategies such as data-enable innovations pose significant challenges. Timely response of communities in LMICs climate risks is also limited due to insufficient access to climate information and early warning systems (Guja and Bedeke, 2024). In addition, traditional beliefs and resistance to change can hinder the acceptance of new adaptation practices especially if cultural norms conflict with proposed strategies (Masud et al., 2017). Further, market failures, such as lack of access to credit and insurance, can deter investments in adaptation while geographical challenges, such as susceptibility to natural disasters, can limit the feasibility of certain adaptation strategies. Addressing these challenges requires a multifaceted approach, including strengthening institutional frameworks, enhancing financial mechanisms, improving access to information and technology, and fostering community engagement. Tailored strategies that consider local contexts and actively involve

TABLE 6 Comparative analysis of climate adaptation strategies in livestock production across different regions.

Adaptation strategy	Country/Region	Implementation approach	Success/Failure	Key factors for success or failure	Impact	Lessons learned	Reference(s)
Silvopastoral systems (SPS)	Montería, Colombia	Intensive rotational grazing combined with planting trees and shrubs to enhance pasture and provide shade.	Success	Innovative grazing techniques; integration of trees for shade and carbon capture; improved animal health.	Improved pasture growth and potential reduction in greenhouse gas emissions.	Financial and technical support are crucial for adoption	Rivera et al. (2019) and Chará et al. (2017)
Breed improvement programs	Northern Kenya	Introduction of crossbred goats (Indigenous × Galla) and sheep (Indigenous × Dorper and Indigenous × Red Maasai) to improve productivity.	Success	Training on productivity measures; improved rainfall; community interest in rebuilding livestock populations.	Increased flock sizes; enhanced reproductive rates.	Breeding programs should consider environmental conditions; within-breed selection may be more appropriate in arid areas.	Ojango et al. (2023)
Water management strategies	Omaheke Region, Namibia	Water harvesting, conservation, drilling boreholes, purchasing water tanks, and digging earth dams to address water scarcity.	Mixed	Financial constraints; limited government support; lack of information on effective strategies.	Variable success in ensuring water availability during dry seasons.	Financial and informational support are essential; community policies should facilitate adaptation measures.	Siririka et al. (2025)
Destocking during drought	Omaheke Region, Namibia	Selling off livestock in anticipation of drought to reduce pressure on resources and generate income.	Failure	Low herd sizes limiting destocking options; cultural value of livestock; unfavorable market prices during droughts.	Limited reduction in livestock losses; financial losses due to poor market conditions.	Early warning systems and market interventions can improve destocking effectiveness; cultural considerations must be addressed.	Siririka et al. (2025)
Disease management training	Northern Kenya	Training pastoral communities in livestock health management to reduce disease incidence.	Success	Community engagement; acceptance of veterinary services and products.	Reduced livestock mortality rates; improved overall herd health.	Ongoing training and accessible veterinary services are critical; integrating traditional knowledge enhances effectiveness.	Ojango et al. (2023)
Climate change adaptation strategies	Northeastern Iran	Implementation of various strategies to adapt to climate change impacts on pastoral livelihoods.	Failure	Social weaknesses; regulatory and insurance challenges; external factors affecting implementation.	Continued vulnerability to climate change impacts; limited improvement in pastoral livelihoods.	Addressing social and regulatory barriers is essential; comprehensive support systems are needed for effective adaptation.	Sharafatmandrad et al. (2024)
Climate-resilient livestock housing	Bangladesh	Elevated flood-proof livestock shelters	Failure	High maintenance costs, lack of farmer adoption	40% of shelters abandoned	Engage farmers in co-designing solutions for better usability	Rahman (2022)

(Continued)

TABLE 6 (Continued)

Adaptation strategy	Country/ Region	Implementation approach	Success/ Failure	Key factors for success or failure	Impact	Lessons learned	Reference(s)
Mobile climate advisory services	Uganda	SMS-based real-time weather forecasts and market info	Success	High mobile phone penetration, public-private partnerships	Reduced livestock losses and increased farm income	Expand digital literacy programs and improve connectivity	Tuheirwe-Mukasa et al. (2019)

stakeholders are essential for effective climate change adaptation in LMICs.

6 Interdisciplinary approaches to climate change adaptation in livestock production

A successful climate change adaptation strategy for livestock production must be multidisciplinary. This approach should incorporate various fields including agricultural sciences, economics, sociology, policy studies, and environmental sciences. Governments and research institutions must foster collaborations across these disciplines to develop policies, technological solutions, and farmer support programs that align with social, economic, and environmental sustainability. By adopting an interdisciplinary approach, LMICs can enhance their adaptive capacity, ensure food security, and promote sustainable livestock production systems in the face of climate change challenges (Sargison, 2020). Social sciences play a crucial role in adaptation efforts by ensuring that strategies align with the knowledge, traditions, and needs of local communities. Effective adaptation requires participatory approaches where livestock farmers, extension officers, and policymakers collaborate to design context-specific solutions (Andrieu et al., 2019). This could be particularly helpful to encourage farmers to participate in initiatives like the community-based breeding programs suggested. In addition, farmer cooperatives and knowledge-sharing networks can enhance resource pooling and dissemination of best practices for adaptation (Eise et al., 2021). Social perspectives could also be key to addressing resistance to new technologies through behavioral change campaigns. Economic strategies are also essential in making adaptation measures financially viable and attractive to livestock producers in LMICs. Governments, financial institutions, and international organizations should invest in mechanisms that support adaptation at different scales. For example, climate insurance and credit access that provide livestock farmers with insurance schemes against climate-induced losses can enhance resilience and encourage investment in climate-smart technologies (Kramer, 2023). Further, market incentives for climate-smart livestock products such as the implementation of certification programs and premium pricing for sustainably produced meat, dairy, and eggs can encourage farmers to adopt adaptive practices. Public-private partnerships (PPPs) in form of collaboration between governments, research institutions, and agribusinesses can also facilitate investment in precision livestock farming, renewable energy integration, and early warning systems. Sustainable adaptation strategies should focus on minimizing the environmental footprint of livestock farming while improving resilience to climate stressors. This could be through agroecological approaches by integrating silvopastoral systems (trees, shrubs, and pasture) into livestock production systems. This can enhance carbon sequestration, improve forage quality, and provide shade to reduce heat stress in livestock. Further, effective water and feed resource management through promotion of rainwater harvesting, efficient irrigation systems, and the use of climate-resilient fodder crops can ensure sustainable feed availability. Further, utilization of livestock waste for biogas energy can reduce methane emissions while providing renewable energy sources for rural farmers.

7 Future research directions

Future studies should explore a range of methodological approaches to deepen our understanding of climate adaptation strategies in livestock production. One promising avenue is field experiments, which can be used to test the effectiveness of various climate adaptation measures, such as precision feeding, heat stress mitigation strategies, and improved pasture management systems. For instance, on-farm trials incorporating climate-resilient livestock breeds could provide empirical evidence on their performance under changing climatic conditions. Farmer surveys and participatory research are also critical for capturing the lived experiences of livestock keepers and their adaptation strategies. Surveys could explore factors influencing the adoption of climate-smart practices, including socio-economic barriers, institutional support, and access to resources. Longitudinal studies tracking how farmers respond to climate variability over time could offer valuable insights into the sustainability of different adaptation strategies.

Moreover, climate modeling and geospatial analysis can be leveraged to predict the impact of climate change on livestock production at regional and national scales. High-resolution climate models can be integrated with livestock productivity data to simulate potential future scenarios which would allow policymakers to design targeted interventions. Additionally, remote sensing and Geographic Information System (GIS) technologies can be employed to monitor changes in rangeland conditions, water availability, and vegetation cover, all of which are crucial for sustainable livestock production. Given the increasing role of technology in climate adaptation, future research should also focus on data-driven innovations such as Internet of Things (IoT)-enabled livestock monitoring, machine learning applications for prediction, and the use of big data analytics to optimize livestock production systems under climate change. Collaborative research involving multidisciplinary teams including animal scientists, climatologists, economists, and social scientists will also be essential in developing holistic and effective adaptation strategies.

8 Conclusion

The livestock sector in LMICs faces significant challenges from climate change, including heat stress, reduced feed availability, increased disease prevalence, and extreme weather events. Addressing these issues requires the implementation of simplified and context-specific adaptation strategies tailored to the unique environmental and socio-economic conditions of LMICs. Key strategies such as the exploitation of indigenous livestock genetic resources, adoption of climate-smart technologies, precision livestock farming and data-enabled innovations, and diversification of livestock species and breeds are essential for building resilience. Successful case studies indicate that when adaptation strategies are well-funded, community-driven, and supported by strong policies, they yield significant improvements in productivity, resilience, and sustainability. However, fragmented policies, socio-economic constraints, and infrastructure gaps remain significant obstacles to adoption and scaling up these initiatives in many LMICs. Targeted investments in research, capacity building, and policy integration are crucial for bridging these gaps. Further, strengthening institutional frameworks, increasing financial support, and fostering public-private partnerships will be key to accelerating climate adaptation efforts. Additionally, ensuring that adaptation strategies are tailored to local contexts through participatory approaches could enhance their effectiveness and long-term sustainability.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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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

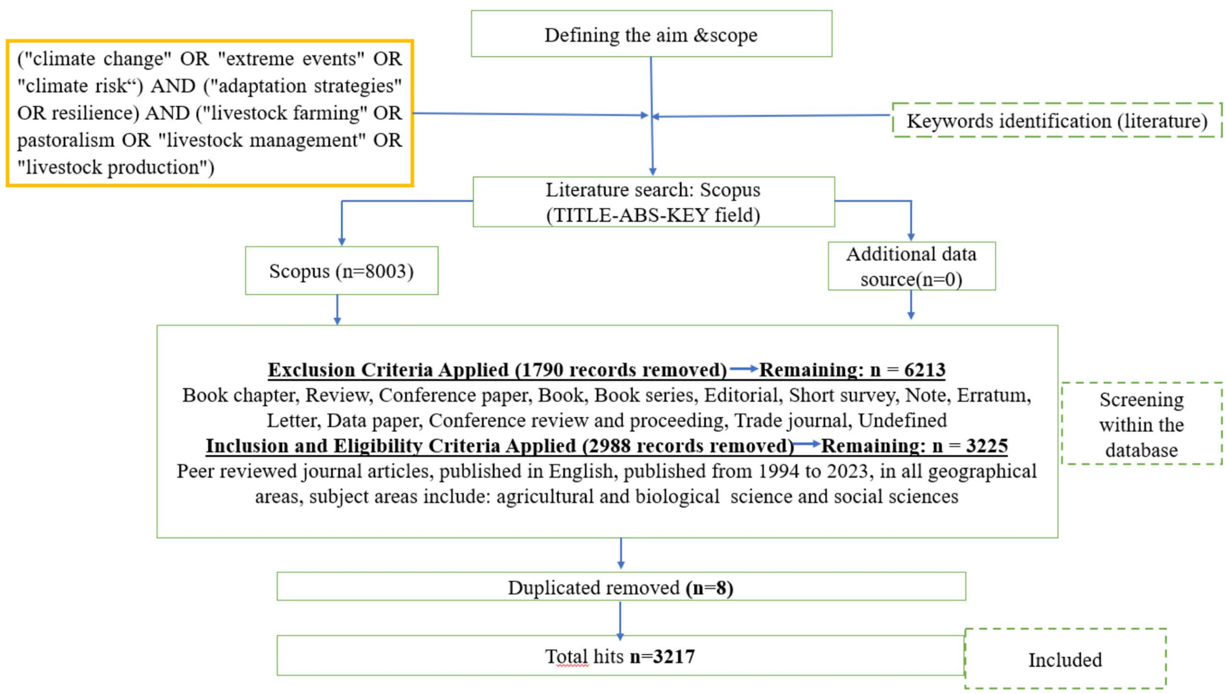

FIGURE 1
Data selection process. Source: Author's compilation.

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.

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.

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.

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

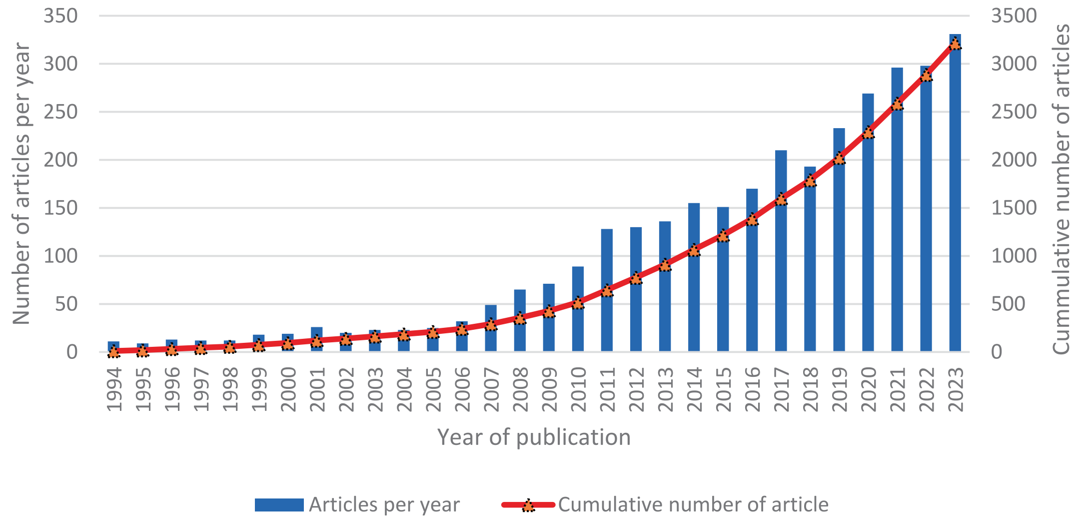

FIGURE 2
Annual and cumulative scientific production from 1994 to 2023. Source: Author's compilation.

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

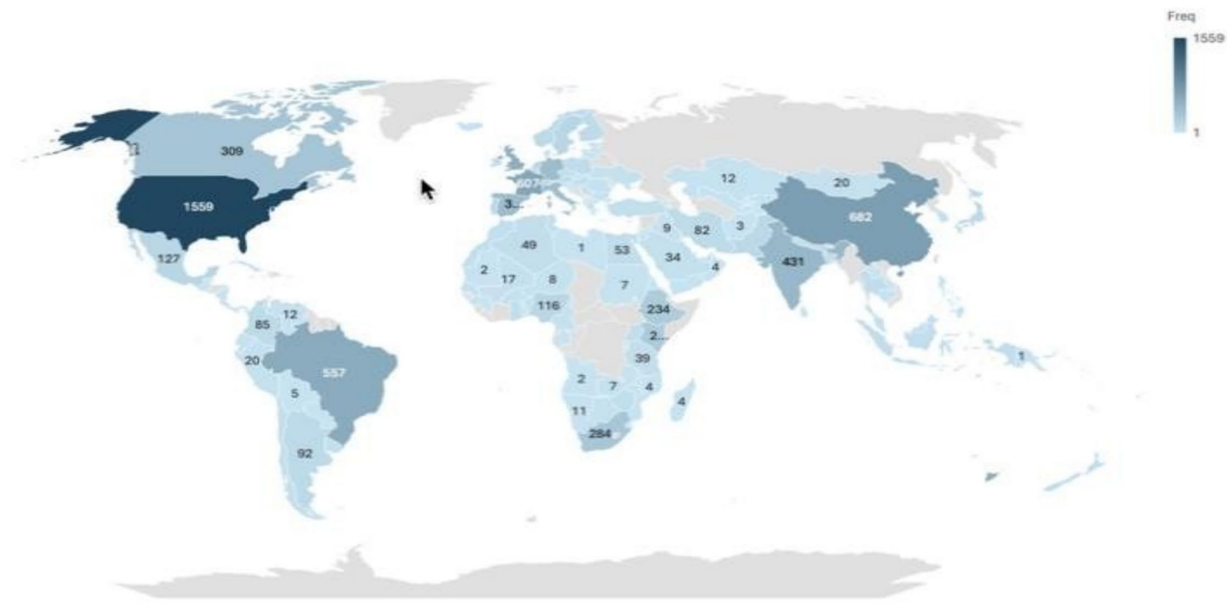

FIGURE 3
Scientific production by country. Various tones of blue represent varying productivity levels: deep blue signifies high productivity, light blue indicates low productivity, and gray denotes an absence of articles. The map was created in Excel. Source: Author's compilation.

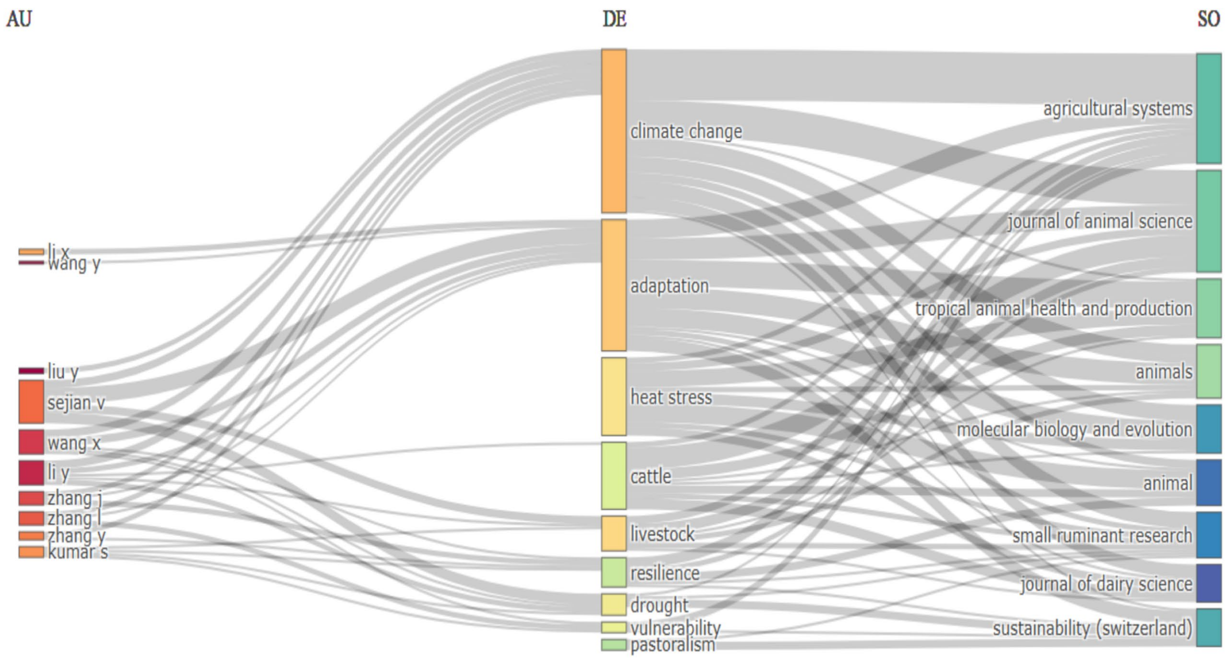

FIGURE 4
Three-field plot illustrating the interconnections between authors (left), authors' keywords (middle), and journals (right). Source: Author's compilation.

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.

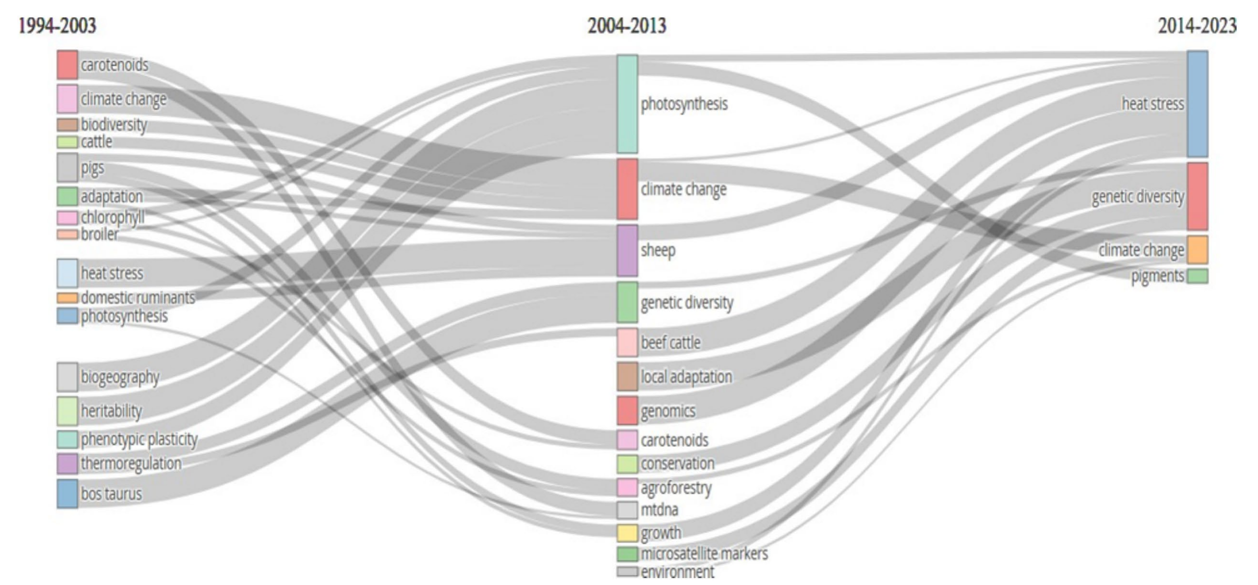

FIGURE 5
Thematic evolution diagram of 1994–2023. Source: Author's compilation.

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

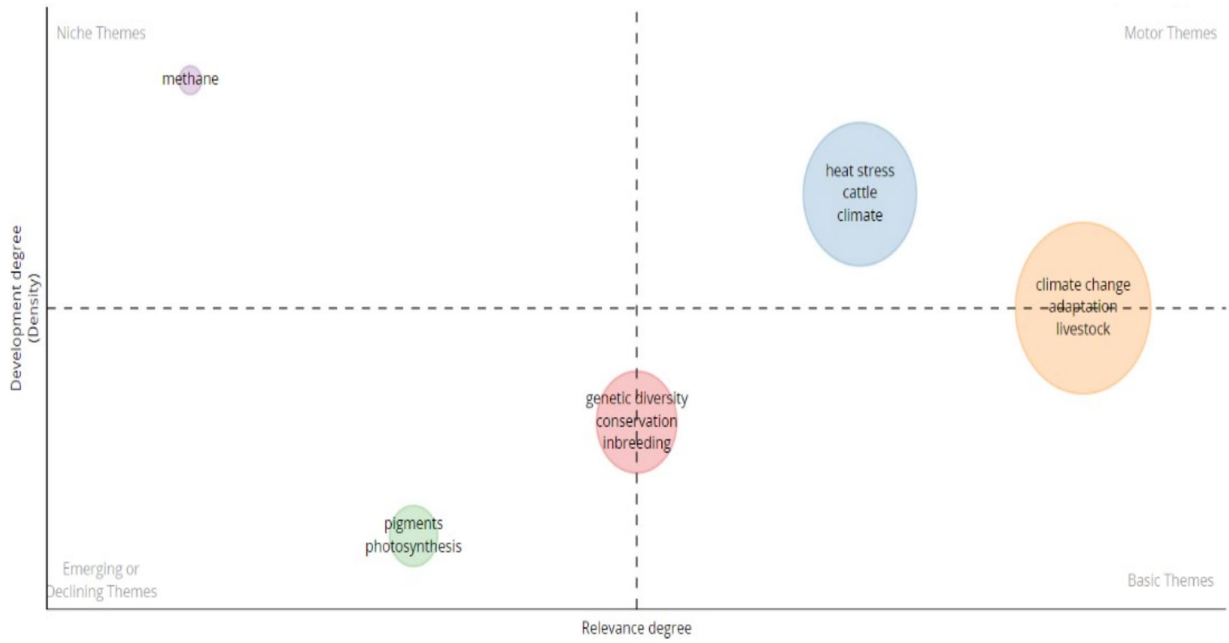

FIGURE 6
Thematic map of 2014–2023. Source: Author's compilation.

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

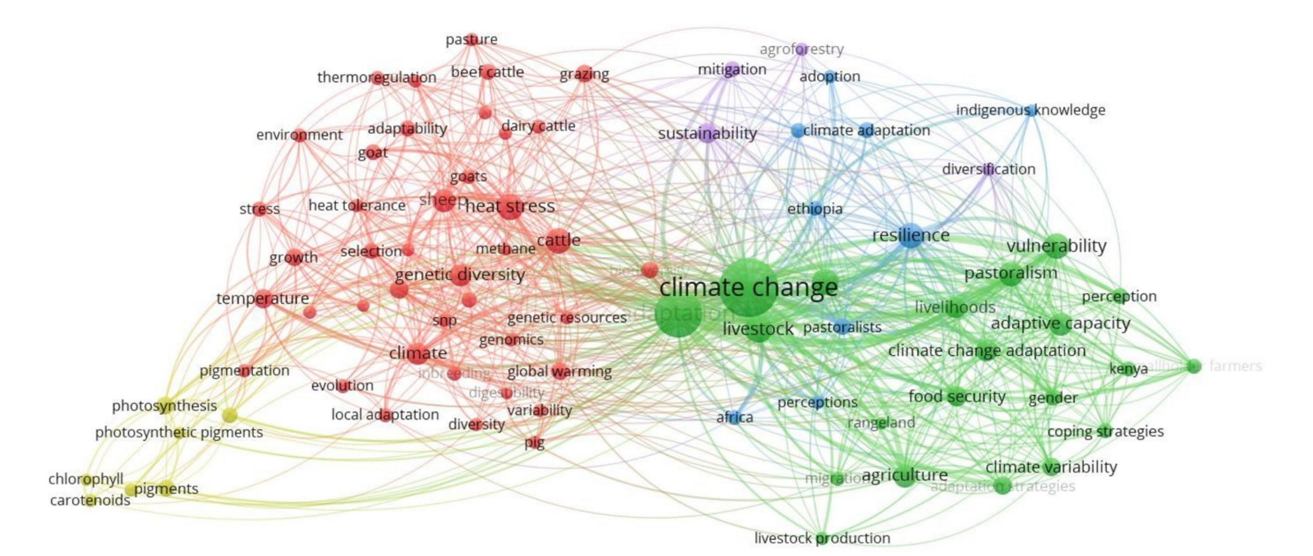

FIGURE 7
Co-occurrence network of author's keywords. Source: Author's compilation.

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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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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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Spatiotemporal heterogeneity and its influencing factors: a perspective on the carbon emissions in China's beef cattle industry

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Based on panel data from 31 provinces in China covering the beef cattle industry from 2009 to 2022, this paper constructs a framework for carbon emission measurement and systematically analyzes the spatial and temporal evolution of carbon emissions, the spatial agglomeration effect, and its driving factors in the beef cattle industry using life cycle assessment, Kernel density estimation, Moran's index, and the spatial Durbin model. The study found that: (1) The total carbon emissions of China's beef cattle industry exhibit a steady growth trend, with significant regional distribution differences. Emissions grow at a slower rate in the eastern region, while the emission levels in the central and western regions, particularly in the western region, are significantly higher than the national average.[1] (2) Carbon emissions exhibit "high-high" and "low-low" spatial agglomeration patterns. Emission reduction is effective in the eastern region, while the central region is gradually catching up. The western region remains the core of high emissions. (3) Carbon emission dynamics indicate a trend of spreading from high-emission regions to peripheral areas, with medium- and small-scale farming regions having greater potential for emission reduction. (4) Improvements in environmental governance, mechanization, and education significantly reduce carbon emissions per unit of beef, driving emission reductions in neighboring regions through spatial spillover effects. Large-scale farming and urban–rural income disparities positively impact carbon emissions, while the role of scientific research inputs in emission reduction remains insignificant in the short term. This study provides a theoretical basis for promoting low-carbon development and regional synergy in the beef industry, suggesting the strengthening of research, development, and promotion of low-carbon technologies, improving the mechanism for regional synergy in emission reduction, and promoting the development of integrated crop-livestock systems to support the realization of the "dual-carbon" goal and the high-quality development of agriculture in the future.

1 Note: Regional classification in this study follows the standard of the National Bureau of Statistics of China, which divides the country into eastern, central, and western regions. The eastern region includes Beijing, Tianjin, Hebei, Shanghai, Jiangsu, Zhejiang, Fujian, Shandong, Guangdong, and Hainan; the central region includes Shanxi, Anhui, Jiangxi, Henan, Hubei, and Hunan; and the western region includes Inner Mongolia, Guangxi, Chongqing, Sichuan, Guizhou, Yunnan, Tibet, Shaanxi, Gansu, Qinghai, Ningxia, and Xinjiang.

KEYWORDS

beef cattle industry, carbon emissions, spatial and temporal evolution, regional disparities, emission reduction pathways

1 Introduction

As global climate change intensifies, controlling and reducing greenhouse gas (GHG) emissions has become a central issue in the global pursuit of sustainable development. The report of the 20th National Congress of the Communist Party of China emphasized that "Chinese-style modernization is the modernization of harmonious coexistence between humanity and nature" (CPC Central Committee, 2022). As an integral component of this vision, the construction of ecological civilization is not only a strategic task, but also a fundamental requirement for building a strong nation and realizing national rejuvenation. As the world's largest developing country, China, facing the dual pressures of sustained economic growth and environmental protection, urgently needs to strike a balance between economic development and ecological protection. In this process, the low—carbon transformation of agriculture, especially the livestock industry, is of particular importance. In accordance with the "Opinions of the Central Committee of the Communist Party of China and the State Council on Comprehensively and Accurately Implementing the New Development Philosophy and Doing a Good Job in Carbon Peaking and Carbon Neutrality" and the "Carbon Peaking Action Plan Before 2030," as well as the relevant arrangements of the "Implementation Plan for Agricultural and Rural Emission Reduction and Carbon Sequestration," emphasis is placed on emission reduction and carbon reduction in the livestock industry. The livestock sector is a significant source of GHG emissions, accounting for approximately 14.5% of global anthropogenic emissions [Gerber et al., 2013; Food and Agriculture Organization of the United Nations (FAO), 2023]. Methane (CH_4), carbon dioxide (CO_2), and nitrous oxide (N_2O) are the primary GHGs emitted by the livestock sector, with CH_4 and N_2O exhibiting much higher global warming potentials (GWP) than CO_2. Consequently, methane and nitrous oxide emissions from the livestock sector play a particularly crucial role in driving global warming. Among major livestock species, cattle (including both beef and dairy) are the largest contributors to methane emissions, primarily through enteric fermentation. Methane produced by cattle accounts for approximately 62% of total livestock-related greenhouse gas emissions [Food and Agriculture Organization of the United Nations (FAO), 2023].[2] In recent years, considerable academic research has concentrated on quantifying and mitigating GHG emissions from the livestock sector. For example, life cycle assessment (LCA) methods have been utilized to assess the carbon footprint of various production systems, providing scientific evidence for global GHG mitigation strategies (Wei et al., 2023). In China, rapid economic development and urban–rural disparities present significant challenges to achieving the nation's "dual carbon" objectives, particularly in the livestock sector (Bai et al., 2021; Yu et al., 2021).

As the scale of beef cattle breeding continues to expand, carbon emissions from the industry have exhibited a persistent upward trend, making it a critical focus for promoting low-carbon transformation in China's agricultural sector. According to official statistics, beef production in China increased from 6.17 million tons in 2015 to 7.53 million tons in 2023, representing a total growth of 22.04%. This continuous growth, while essential for ensuring domestic meat supply, has also intensified environmental pressures. Therefore, achieving emission reduction in this sector is not about limiting production, but about improving production efficiency, promoting green technologies, and strengthening coordinated policy support. Since the carbon emissions of the beef cattle industry account for a large proportion of livestock farming emissions, its emission reduction potential has become the key to promoting the green transformation of agriculture (Chen et al., 2020; He et al., 2023). The report of the 20th National Congress of the Communist Party of China pointed out that it is necessary to accelerate the construction of a modern economic system and promote the high—quality development of agriculture, emphasizing "promoting green development and building a new pattern of modernization for harmonious coexistence between humanity and nature." Against this strategic backdrop, promoting the low—carbon transformation of the beef cattle industry has become one of the important measures for China to achieve high—quality agricultural development (Li and Yang, 2024). The beef cattle industry, a key component of the livestock sector, exhibits complex and regionally heterogeneous sources of GHG emissions. Major emission sources include enteric fermentation, manure management, and feed production, with enteric fermentation contributing most to methane emissions in beef cattle (Tongwane and Moeletsi, 2020). Furthermore, manure management generates significant nitrous oxide emissions, while feed production emits both carbon dioxide and nitrous oxide (Pelton et al., 2024). GHG emissions from beef cattle production have been rising globally, driven by increasing demand for beef. This trend is particularly evident in China, where rising income levels and shifts in meat consumption patterns have led to a significant increase in GHG emissions from beef cattle farming (Xu et al., 2019). Simultaneously, there are significant regional differences in carbon emission efficiency. Previous studies have shown that among the major livestock products in China, beef has the highest greenhouse gas (GHG) emission intensity per kilogram of meat, followed by mutton, chicken, and pork (Wei et al., 2023). In addition, a dietary carbon footprint analysis based on protein content indicated that beef possesses the largest per-unit carbon footprint, with lamb and pork ranking second and third, respectively (Li et al., 2024). For instance, in Yan and Zhang (2023), the carbon emission efficiency in China's primary beef-producing regions exhibited a spatial pattern of higher efficiency in the east and lower efficiency in the west, highlighting significant regional disparities in mitigation capacity. Similarly (Du et al., 2024), estimated emissions across various regions in China,

2 Note: According to the Food and Agriculture Organization of the United Nations (FAO) (2023) report, cattle (including both beef and dairy) emit approximately 3.8 gigatons of CO_2-equivalent annually, representing 62% of total greenhouse gas emissions from the global livestock sector. Pigs, chickens, buffaloes, and small ruminants account for 14, 9, 8, and 7%, respectively. By product type, meat contributes about two-thirds of total emissions, while milk accounts for around 30%, and eggs make up the remainder.

finding that the central and western regions lag far behind the eastern coastal areas in both emission intensity and the implementation of mitigation measures. Some scholars also demonstrated that feed selection and management practices in U.S. beef cattle production systems are critical in determining GHG emissions (Rotz et al., 2019). Therefore, in-depth research on the emission characteristics and influencing factors of the beef cattle industry is crucial for understanding regional carbon emission dynamics and providing a scientific foundation for region-specific mitigation policies.

Building upon the substantial scholarly progress in GHG emissions research within livestock systems, certain complexities in beef cattle production still warrant more nuanced analysis to deepen our understanding. First, most studies focus on emissions at the macro level, lacking in-depth investigations into regional heterogeneity and the emission reduction potential of underdeveloped areas (Jin et al., 2020). This gap in understanding hinders the formulation of precise and effective mitigation policies tailored to regional conditions. Second, studies on the drivers of GHG emissions often focus on individual variables, such as technological investment or production scale (Pelton et al., 2024), without sufficiently addressing the complex interactions between economic development, policy support, and technological advancement. Therefore, future research should focus more on regional collaborative governance, the effects of environmental policies, and the comprehensive impact of technological innovation on carbon emissions, particularly in underdeveloped areas, while exploring adaptable and effective emission reduction measures and policies. Additionally, feasible solutions should be proposed to overcome barriers in promoting low-carbon technologies, such as insufficient infrastructure, lack of funding, and inadequate technical training. Regarding technology, research should concentrate on advancing the application of low-carbon aquaculture technologies such as feed optimization, manure treatment, and energy efficiency improvements, and develop targeted emission reduction pathways based on local resource endowments and economic foundations to ensure the effectiveness and sustainability of GHG emissions reduction in different regions. Through differentiated policies and technological support, it is anticipated that the beef cattle industry will transform towards a greener and more sustainable direction, achieving simultaneous improvements in emissions reduction and production efficiency.

2 Measurement of carbon emissions, data sources, and research methods

2.1 Measurement boundary of carbon emissions

This study employs the LCA method in combination with carbon emission coefficients to comprehensively assess the carbon emissions of the beef cattle industry chain in China, based on its actual development conditions (Shi et al., 2022; Ma and Xiao, 2024). The beef cattle industry is divided into three primary stages: upstream cultivation, midstream farming, and downstream processing. The carbon emissions from each stage are calculated based on its primary sources, including feed crop cultivation, feed transportation and processing, enteric fermentation in beef cattle, manure management systems, energy consumption during cattle farming, and beef product processing (D'aurea et al., 2021; Liang and Wang, 2024; Wu et al., 2022). The carbon emission factors involved in the calculation process are detailed in Appendix.

2.2 Calculation of carbon emissions in specific stages

2.2.1 Upstream cultivation stage

2.2.1.1 Feed crop cultivation

Beef cattle feed mainly consists of roughage (e.g., straw, silage corn) and concentrate feed (e.g., corn, soybean meal, wheat bran). Among these, soybean meal and wheat bran are by-products of soybean and wheat, so only the carbon emissions from corn cultivation are considered (O'Brien et al., 2020; Wu et al., 2021; Tian et al., 2014). The emissions are calculated using the following formula:

$$CO_{2\text{feed}} = \sum_{u=1}^{n} P \cdot C_{\text{feed}} \cdot S_u \cdot F_{\text{feed}} \quad (1)$$

In Equation 1, p represents the annual beef production (unit: tons); C_{feed} represents the feed consumption coefficient per unit of beef product (unit: kg/kg); S_u represents the proportion of corn in concentrate feed (unit: %); F_{feed} represents the CO_2 emission factor during the cultivation process of type u grain.

2.2.1.2 Feed transportation and processing

Feed ingredients (e.g., corn, soybeans, wheat) are transported from production sites to processing facilities, where they undergo cleaning, grinding, mixing, and other processing steps. This process involves significant energy consumption, resulting in corresponding greenhouse gas emissions. The calculation formula is as follows:

$$CO_{2transport} = \sum_{u=1}^{n} P \cdot C_{feed} \cdot S_u \cdot F_{transport} \quad (2)$$

In Equation 2, $F_{transport}$ represents the carbon emission factor for feed transportation and processing, while the definitions of other variables remain the same as previously described.

2.2.2 Midstream farming stage

2.2.2.1 Enteric fermentation of beef cattle

As ruminants, beef cattle produce significant amounts of methane (CH_4) during their enteric fermentation process, which is a major source of carbon emissions in the livestock sector.

$$CO_{2\,fermentation} = N \cdot E_{CH_4\,fermentation} \cdot GWP_{CH_4} \quad (3)$$

In Equation 3, N represents the average annual number of beef cattle (unit: head); $E_{CH_4\,fermentation}$ represents the emission factor for enteric fermentation in beef cattle (unit: kg/head); GWP_{CH_4} represents the global warming potential of CH_4, with a value of 21.

2.2.2.2 Manure management system

During the storage and treatment of beef cattle manure, both methane (CH_4) and nitrous oxide (N_2O) are emitted. The emissions of these two gases are calculated separately and then summed.

$$CO_{2management} = CH_4 + N_2O = N \cdot ECH_{4management} \cdot GWPCH_4 + N \cdot EN_2O_{fermentation} \cdot GWPN_2O \quad (4)$$

In Equation 4, $ECH_{4management}$, $EN_2O_{fermentation}$ represent the emission factors for CH_4, N_2O in the manure management system, respectively; $GWPCH4$ represents the global warming potential (GWP) of CH_4, with a value of 21; GWP_{N_2O} represents the global warming potential (GWP) of N_2O, with a value of 310.

2.2.2.3 Energy consumption in beef cattle farming

During the beef cattle farming process, significant amounts of electricity and coal are consumed to maintain the operation of facilities, such as temperature control, ventilation, and manure treatment, which results in carbon dioxide emissions. The calculation formula is as follows:

$$CO_{2energy} = N \cdot \frac{\cos t_{electricity}}{price_{electricity}} \cdot F_{electricity} \cdot N \cdot \frac{\cos t_{coal}}{price_{coal}} \cdot F_{coal} \quad (5)$$

In Equation 5, $\cos t_{electricity}$ and $\cos t_{coal}$ represent the electricity cost and coal cost per head of beef cattle, respectively; $price_{electricity}$ and $price_{coal}$ represent the unit prices of electricity and coal, respectively; $F_{electricity}$and $Fcoal$ represent the CO_2 emission factors for electricity consumption and coal combustion, respectively.

2.2.3 Downstream processing stage

During the process of beef production from slaughter to market sale, multiple processing stages, such as slaughtering and packaging, are involved. The energy consumption and associated carbon emissions of each stage need to be accounted for. The calculation formula is as follows:

$$CO_{2processing} = Q \cdot \frac{F_{processing}}{e} \cdot F_{electricity} \quad (6)$$

In Equation 6, $F_{processing}$ represents the energy consumption coefficient per unit of beef product for the processing stage; $F_{electricity}$ represents the CO_2 emission factor for electricity consumption.

2.3 Total carbon emissions calculation for the beef cattle industry

Following the life cycle assessment (LCA) framework, total carbon emissions from the beef cattle industry are calculated as the sum of emissions across all production stages, as shown in the formula below:

$$TOTAL_{CO_2} = CO_{2feed} + CO_{2transport} + CO_{2fermentation} + CO_{2management} + CO_{2energy} + CO_{2processing} \quad (7)$$

In Equation 7, each term represents the CO_2, CH_4, and N_2O emissions generated from respective stages, including feed cultivation, enteric fermentation, manure management, energy consumption, and processing. By summing up the emissions from all stages, the total carbon emissions of the beef cattle industry are obtained.

2.4 Data sources

This study utilizes data from 31 provinces in China (excluding Hong Kong, Macau, and Taiwan) spanning from 2009 to 2022 to investigate the carbon emissions of the beef cattle industry. The data primarily come from sources such as the China Rural Statistical Yearbook, the Statistical Bulletin of the People's Republic of China on National Economic and Social Development, the National Compilation of Cost–Benefit Data of Agricultural Products, the Statistical Yearbook of China's Population and Employment, the Statistical Yearbook of China, the Statistical Yearbook of China's Environment, the Statistical Yearbook of China's Ecological Environment, and the statistical yearbooks of provinces and cities. The data used to analyze the impact factors of carbon emissions primarily derive from relevant literature and official statistics, including the China Environmental Statistics Yearbook, the China Ecological Environment Statistics Yearbook, the China Statistical Yearbook, the China Rural Statistics Yearbook, the China Agricultural Statistics Yearbook, the China Population and Employment Statistics Yearbook, and the China Animal Husbandry and Veterinary Statistics Yearbook.

2.5 Research methods

2.5.1 Spatiotemporal evolution analysis of carbon emissions in the beef cattle industry

To comprehensively analyze the dynamic evolution characteristics of carbon emissions in the beef cattle industry across Chinese provinces, this study employs the Kernel Density Estimation method. This method effectively estimates and analyzes the distribution patterns of carbon emissions in different regions, revealing their spatiotemporal evolution trends (Tian et al., 2024). By using this method, the study visually demonstrates the changes in the distribution of carbon emissions across provinces at various time points. This helps to further identify and understand the dynamic evolution patterns of carbon emissions. The analysis provides robust data support for subsequent policy recommendations and industrial development, offering valuable references for local governments to formulate more precise carbon emission control policies (Wen et al., 2024).

2.5.2 Analysis of factors influencing carbon emissions in the beef cattle industry

To examine the factors influencing carbon emissions in the beef cattle industry, a spatial econometric model is constructed. This model simultaneously accounts for spatial dependencies and temporal effects, uncovering both the direct and indirect influences of various factors on carbon emissions. The specific formulation is as follows:

$$Y_i = \rho W Y_i + X_i \beta + \theta W X_i + \varepsilon_i \quad (8)$$

In Equation 8, Y_i represents the per-unit carbon emissions of beef production in region i; ρ is the spatial autoregressive coefficient, representing the spatial lag effect of the dependent variable in neighboring regions; W is the spatial weight matrix, describing the spatial relationships between different regions; X_i represents the explanatory variables for region i; β is the coefficient of the explanatory variables, indicating the impact of each explanatory variable on carbon emissions in region i; θ is the spatial lag coefficient of the independent variables, reflecting the influence of the independent variables in neighboring regions on carbon emissions in region i; ε_i is the error term for region i.

3 Carbon emission measurement results and spatial differentiation characteristics of the beef cattle industry

3.1 Trends in carbon emissions

By calculating the carbon emissions from beef cattle production across 31 provinces from 2009 to 2022, it is observed that national carbon emissions in the beef cattle industry show a steady upward trend (Table 1). The total emissions increased from 96.98 million tons in 2009 to 140.55 million tons in 2022, with an average annual growth rate of 2.90%. Specifically, carbon emissions in the eastern region grew at the slowest rate, with an average annual growth rate of just 1.31%. This reflects the region's advanced adoption of intensive farming practices and low-carbon livestock technologies. In the central region, carbon emissions also increased relatively modestly, with an average annual growth rate of 0.42%, suggesting that emission reduction measures have achieved some success. However, the western region experienced the fastest growth in carbon emissions, with an average annual growth rate of 4.08%. This is primarily attributed to extensive farming practices and grazing-based livestock systems prevalent in the region, which have led to substantial increases in emissions. These findings emphasize the considerable challenges that the western region continues to face in achieving effective emission reductions.

In the various stages of the beef cattle industry, carbon emissions from the upstream cultivation stage, primarily stemming from feed crop cultivation, increased significantly from 10.7318 million tons to 17.0982 million tons, with an average annual growth rate of 3.65% (Table 2). This notable growth is closely linked to the rising demand for feed and the expansion of cultivation areas. The midstream farming stage also saw an increase in carbon emissions, with enteric fermentation and manure management systems as the primary sources. The increase in emissions from these two processes is closely linked to the expansion of farming scale and the release of greenhouse gases. The average annual growth rate for this stage was 2.78%. However, the relatively moderate growth reflects the adoption of emission reduction technologies in some regions. In contrast, carbon emissions from the downstream processing stage grew at the slowest rate, rising from 0.74 million tons to 0.85 million tons, with an average annual growth rate of only 1.06%. This suggests that emissions in this stage remain relatively low, with limited potential for further reductions. Overall, the majority of carbon emissions in the beef cattle industry are concentrated in the upstream cultivation and midstream farming stages, while emissions from the downstream processing stage exhibit slower, more stable growth. These findings underscore the need to focus emission reduction efforts on feed cultivation and farming practices to maximize the industry's potential for carbon mitigation.

TABLE 1 Changes in carbon emissions of the national and eastern, central, and western beef cattle industry from 2009 to 2022 (unit: ten thousand tons CO_2-eq).

Year	National	Eastern	Central	Western
2009	9697.52	1529.48	2248.88	4986.83
2010	10832.03	1709.53	2487.88	5367.41
2011	10673.09	1654.40	2424.54	5342.82
2012	10832.68	1675.92	2538.23	5349.17
2013	10984.68	1681.39	2611.17	5453.45
2014	11333.68	1681.70	2658.68	5719.24
2015	11797.26	1765.02	2774.46	5939.51
2016	11912.76	1795.30	2715.77	6099.60
2017	10764.79	1391.41	1627.57	6435.89
2018	10841.60	1435.29	1636.31	6449.66
2019	11652.86	1504.22	1748.97	6887.21
2020	12708.31	1681.58	2102.58	7644.22
2021	13177.83	1702.81	2237.27	7889.44
2022	14054.65	1811.93	2376.14	8387.08
Average growth rate	2.90%	1.31%	0.42%	4.08%

TABLE 2 Changes in carbon emissions at different stages of the national beef cattle industry from 2009 to 2022 (unit: ten thousand tons CO_2-eq).

Year	Upstream cultivation stage		Midstream farming stage			Downstream processing stage
	Feed crop cultivation	Feed transportation & processing	Enteric fermentation	Manure management	Energy consumption in farming	Beef product processing
2009	1073.18	19.88	6711.92	1755.81	135.99	0.74
2010	1024.54	18.98	7641.91	1999.09	146.76	0.74
2011	1010.89	18.73	7537.02	1971.65	134.08	0.72
2012	1076.57	19.95	7595.65	1986.99	152.81	0.73
2013	1027.86	19.05	7754.97	2028.67	153.41	0.72
2014	1082.80	20.06	7984.38	2088.68	157.02	0.73
2015	1071.02	19.84	8360.87	2187.17	157.63	0.73
2016	1089.57	20.19	8438.09	2207.37	156.81	0.73
2017	1135.43	21.04	7504.70	1963.20	139.67	0.75
2018	1203.29	22.30	7505.27	1963.35	146.64	0.76
2019	1448.08	26.83	7935.73	2075.96	165.47	0.79
2020	1504.52	27.88	8714.90	2279.78	180.43	0.79
2021	1515.74	28.09	9076.99	2374.51	181.69	0.82
2022	1709.82	31.68	9586.95	2507.91	217.45	0.85
Average growth rate	3.65%	3.65%	2.78%	2.78%	3.68%	1.06%

3.2 Spatial differentiation characteristics of carbon emissions

In this study, ArcGIS visualization maps were used to illustrate the spatial patterns and temporal trends of carbon emissions across provinces for the years 2009, 2013, 2017, and 2022 (Figure 1). These maps provide an intuitive depiction of interprovincial differences, employing color gradients to reflect the relative intensity of carbon emissions over time. Overall, with the promotion of intensive farming practices and the implementation of green technologies and policies, carbon emissions from China's beef cattle industry have gradually decreased, especially in the eastern and central regions, where emission reduction efforts have been most successful. Specifically, from 2009 to 2013, carbon emissions remained high nationwide, particularly in the western and northern regions, such as Inner Mongolia and Qinghai, which are key livestock farming areas. Emissions in these regions remained consistently high due to extensive grazing practices. However, following the adoption of intensive farming practices and green technologies after 2017, particularly in the eastern provinces, carbon emissions have steadily declined annually, highlighting the effectiveness of green production technologies and modern management practices.

Nonetheless, the western and central regions have exhibited slower progress in reducing emissions. Specifically, the western region, despite demonstrating some reduction in carbon emissions by 2022, continues to exhibit relatively high levels. This suggests that these regions continue to face significant challenges in reducing emissions, primarily due to traditional grazing practices, low production efficiency, and delays in the adoption of advanced technologies and policies. Overall, the eastern region has achieved the most significant reductions in carbon emissions, primarily due to the implementation of intensive farming practices, technological advancements, and strong policy guidance. In contrast, while the western and central regions possess considerable potential for emission reductions, achieving substantial progress will require greater efforts and increased support to meet reduction targets.

In analyzing carbon emissions, the kernel density map offers a clearer perspective on the distribution of carbon emissions across different periods and regions, with particular focus on changes in the distribution of per-unit beef carbon emissions. This study utilizes the kernel density estimation method to illustrate the distribution characteristics of sample data across regions. By plotting the kernel density distribution curves for the entire country and the three major regions, the analysis examines the position of the density curves, the shape of the main peaks, the extent of distribution, and the number of peaks. As illustrated in Table 3 and Figure 2, the kernel density curves of carbon emissions per kilogram of beef across China and its regions from 2009 to 2022 exhibit an initial rightward shift followed by a leftward shift, reflecting that carbon emissions initially increased and subsequently decreased. This change signifies that China has attained significant progress in implementing low-carbon policies and advancing technological improvements, thereby laying a strong foundation for achieving the "dual carbon" goals. Additionally, the main peak of the kernel density curve gradually decreases in height and widens, indicating substantial regional variations in carbon peak trajectories and timing across China.

At the regional level, the range of variation in the kernel density curve for the eastern region remains limited. The peak position is concentrated in the low-emission interval, and the right-tail

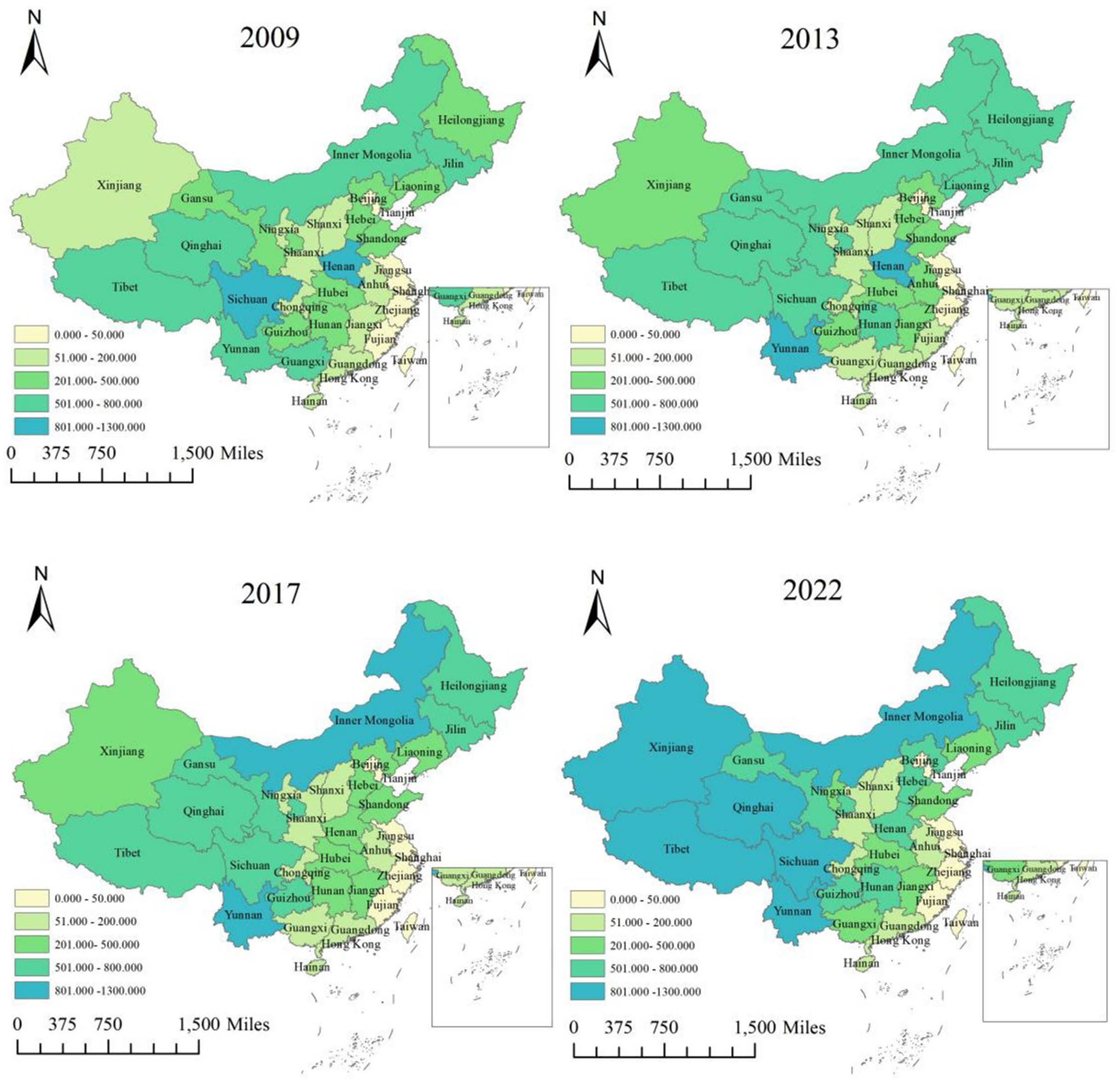

FIGURE 1
Spatial distribution of carbon emissions from the national beef cattle industry in each province.

TABLE 3 Dynamic evolution characteristics of agricultural carbon emissions in china and the eastern, central, and western regions.

Indicator	National	Eastern Region	Central Region	Western Region
Distribution position	First shifts right, then left	First shifts right, then left	First shifts right, then left	First shifts right, then left
Peak distribution shape	Height decreases, width widens gradually	Height decreases, width remains stable	Height first rises, then falls, width remains stable	Height decreases, width widens gradually
Distribution extension	Right tail significantly contracts	Right tail significantly contracts	Right tail significantly widens	Left tail significantly contracts
Number of peaks	Single peak	Single peak	Single peak	Single or double peak

distribution has substantially converged, indicating that internal differences in carbon emissions within the region are gradually narrowing, although emission reduction pressures remain significant. The kernel density curve for the central region exhibits a main peak characteristic of "initial increase followed by a decrease," with little change in width. This suggests that internal differences in emissions within the region are stable; however, some provinces continue to exhibit high emissions, and progress in emission reductions remains sluggish. In the western region, the kernel density curve demonstrates a decreasing main peak height and increasing width, with a

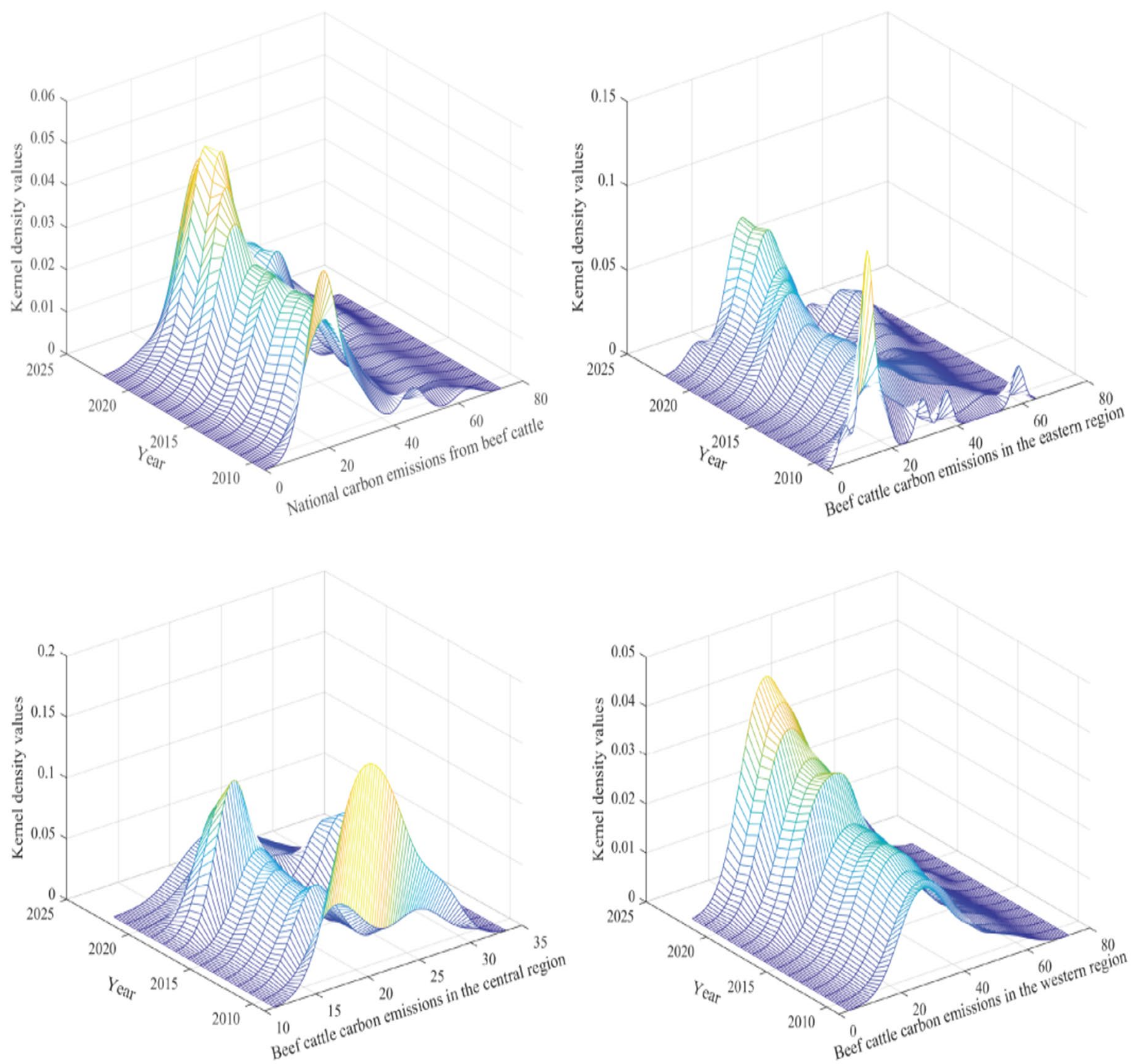

FIGURE 2
The dynamic evolution of the distribution of carbon emissions per kilogram of beef in the whole country and the eastern, central and western regions.

"double-peak" phenomenon observed in certain years, indicating a degree of carbon emission polarization within the region.

In terms of distributional extensibility, a common right-tailing phenomenon is observed across the country and in all regions, indicating the presence of high-emission values across regions. Among these, the right-tailing in the eastern region is relatively well-contained. The central region exhibits limited distributional extensibility, while the western region gradually demonstrates a left-tailing characteristic, indicating significant reductions in carbon emissions in certain provinces. The possible reasons for these patterns can be attributed to the following factors: the eastern region benefits from technological innovation and policy support, facilitating a relatively rapid carbon emission reduction process. As a major grain-producing area, the central region's industrial structure includes a higher proportion of extensive farming practices, complicating efforts to reduce emissions. In contrast, the western region, characterized by substantial ecological and economic disparities, exhibits significant internal imbalances in carbon emissions. These differences suggest that achieving balanced agricultural carbon-emission reductions across the country requires further advancement in policy making and technology dissemination tailored to local conditions. Additionally, greater resource allocation and enhanced support should be directed toward the central and western regions to better align regional development with the realization of the carbon-neutrality goal.

3.3 Spatial correlation test based on Moran's index

Through an analysis of the overall carbon emissions of China's beef cattle industry, this study highlights the spatial distribution and dynamic changes in carbon emissions at both the national and regional levels. Although total carbon emissions reflect the overall emission levels of a specific region or industry, they fail to adequately capture the relationship between emissions and outputs, particularly the variations in beef production scale, efficiency, and production

TABLE 4 Moran's I index results.

Year	Adjacency matrix		Geographic distance matrix		Spatial economic-geographic nested matrix	
	Moran'I	Z-value	Moran'I	Z-value	Moran'I	Z-value
y2009	0.331***	3.228	0.111***	4.384	0.100**	2.687
y2010	0.256**	2.545	0.108***	4.237	0.103**	2.727
y2011	0.328***	3.230	0.129***	4.964	0.148***	3.672
y2012	0.358***	3.440	0.135***	5.062	0.156***	3.776
y2013	0.344***	3.334	0.130***	4.925	0.149***	3.656
y2014	0.349***	3.362	0.135***	5.059	0.154***	3.741
y2015	0.356***	3.364	0.136***	4.992	0.153***	3.647
y2016	0.352***	3.336	0.129***	4.804	0.142***	3.441
y2017	0.324***	3.189	0.122***	4.736	0.128***	3.273
y2018	0.353***	3.362	0.128***	4.798	0.137***	3.362
y2019	0.412***	3.787	0.143***	5.128	0.155***	3.634
y2020	0.451***	4.133	0.146***	5.233	0.152***	3.593
y2021	0.489***	4.428	0.158***	5.542	0.163***	3.781
y2022	0.506***	4.559	0.161***	5.620	0.162***	3.743

*, **, *** denote statistical significance at the 10%, 5%, and 1% levels, respectively.

methods across regions. Consequently, relying solely on total carbon emissions to evaluate the green development levels of different regions introduces inherent limitations. To more accurately assess the carbon emissions of the beef cattle industry in each region and establish a direct connection with regional economic development and environmental sustainability, this study employs per-unit beef carbon emissions as a refined and standardized indicator. This approach provides a more meaningful analytical perspective, offering insights that are highly relevant to practical application (Wu, 2015).

This study systematically investigates the spatial dependence of per-unit beef carbon emissions through Moran's Index. Considering that the spatial autocorrelation of carbon emissions may be influenced by both geographical and economic distances, this study employs three types of spatial weight matrices: the adjacency matrix, the geographical distance matrix, and the spatial economic-geographical nested matrix. The Moran's Index for each year is calculated using global spatial autocorrelation analysis (Table 4). From 2009 to 2022, the Moran's Index values for all three matrices remained positive and statistically significant, confirming the presence of spatial autocorrelation in per-unit beef carbon emissions. Specifically, the Moran's Index values increased over time and consistently remained significant at the 1, 5%, or 10% levels each year. For instance, in 2009, the Moran's Index values for the adjacency matrix, geographical distance matrix, and spatial economic-geographical nested matrix were 0.331, 0.111, and 0.100, respectively, indicating a notable degree of spatial clustering in per-unit beef carbon emissions. By 2022, these values had risen to 0.506, 0.161, and 0.162, reflecting a stronger and more stable spatial autocorrelation in per-unit emissions over time. This spatial dependence implies that carbon emission levels in one region are shaped not only by its own development but also by the emission levels and policies of neighboring regions. Therefore, policymakers must consider these spatial linkages and coordinate emission reduction measures at the regional level to enhance the effectiveness of low-carbon development.

4 Influence factors study

4.1 Logical analytical framework

According to green development theory, promoting a low-carbon economy is central to achieving sustainable development. As a key component of animal husbandry, the carbon emission characteristics of the beef cattle industry are directly linked to achieving the "dual-carbon" goals. This study examines the key factors influencing carbon emissions per unit of beef from multiple perspectives and explores their spatial heterogeneity. The level of economic development is a significant factor influencing carbon emissions (Table 5). According to the Environmental Kuznets Curve (EKC) theory, economically developed regions are more likely to adopt green technologies and low-carbon production models earlier, thereby effectively reducing carbon emissions per unit. In contrast, regions characterized by a significant urban–rural income gap often experience inefficient resource allocation and irrational consumption patterns, resulting in higher carbon emissions per unit. Technological progress plays a crucial role in carbon reduction, particularly improvements in research funding, mechanization, and technical expertise. These advancements optimize resource utilization and production processes, effectively reducing carbon emissions per unit of output e (Ning et al., 2023). However, in some regions, short-term research investments may not directly result in productivity gains, and improvements in mechanization may lead to inefficient energy consumption if not coupled with green technologies.

Large-scale farming has the potential to reduce carbon emissions per unit by lowering marginal costs and enhancing resource use

TABLE 5 Variable definitions and descriptive statistics.

Symbol	Indicator name (unit)	Observations	Mean	Standard deviation
Carbon	Carbon emissions per kilogram of beef (CO_2 equivalent)	434	19.9014	13.1368
Envi	Environmental governance (100 million yuan)	434	269.5737	211.6727
Econ	Economic development level (100 million yuan)	434	977.1505	755.2655
Invest	Livestock research funding (100 million yuan)	434	15.5151	15.4257
Mech	Total mechanical power in livestock (10,000 kw)	434	974.7198	909.9718
Scale	Degree of scale (number)	434	0.0071	0.0169
Educ	Education level (years)	434	7.7899	0.7841
Consu	Per capita beef consumption (kg)	434	2.2337	3.0110
Inco	Urban–rural income gap (%)	434	2.6666	0.4789
Tech	Professional technical level (%)	434	0.7327	0.2174

efficiency. However, this benefit can be offset if environmental protection technologies are not adequately integrated, potentially leading to increased overall carbon emissions. Additionally, per capita beef consumption plays a significant role in determining production intensity. In regions with higher demand, increased production pressure often results in elevated carbon emissions. Furthermore, environmental governance and education levels are crucial social factors influencing carbon reduction. Effective environmental governance can improve resource use efficiency through targeted policy guidance, creating positive spillover effects that benefit surrounding areas (Shi and Wang, 2024). Similarly, improving education levels can enhance public environmental awareness, facilitate the adoption of green technologies, and indirectly reduce carbon emissions per unit.

According to spatial economics theory, carbon emissions per unit of beef exhibit significant spatial heterogeneity due to differences in natural resource endowments, economic development levels, and technological capabilities. In the eastern region, which is economically developed and has widely adopted green technologies, carbon emission levels are lower. In contrast, the western region, characterized by traditional farming methods and lower production efficiency, experiences higher carbon emissions. This study constructs a multi-dimensional analytical framework that incorporates factors such as economic development, technology, scale, environmental governance, education, and consumption. The goal is to explore how these factors influence carbon emissions per unit of beef using a spatial econometric model, revealing their spatial heterogeneity. The findings aim to provide both theoretical and empirical support for the formulation of targeted low-carbon policies.

4.2 Model specification

When selecting a spatial econometric model, it is crucial to perform correlation tests on the data to identify the most appropriate model. This study employs the Hausman test to determine whether a fixed effects model or a random effects model is more suitable (Table 6). The test results show that, at the 1% significance level, the null hypothesis is rejected, indicating that the random effects model is not appropriate. As a result, the fixed effects model is chosen as the preferred model. In addition, the study conducts Lagrange Multiplier (LM) tests, Wald tests, and Likelihood Ratio (LR) tests to further validate the selection of the spatial econometric model. Building on the traditional Spatial Autoregressive Model (SAR) and Spatial Error Model (SEM), the Spatial Durbin Model (SDM) is deemed more appropriate for this research. The test results demonstrate that the Spatial Durbin Model more effectively captures spatial correlations, aligning with the research requirements. The specific test results are as follows:

TABLE 6 Variable definitions and descriptive statistics.

Test indicator	Test statistic	*p*-value
LM-error	287.03	0.00
Robust LM-error	21.46	0.00
LM-lag	280.96	0.00
Robust LM-lag	15.4	0.00
LR-error	59.31	0.00
LR-lag	55.85	0.00
Wald-error	52.33	0.00
Wald-lag	53.97	0.00
Hausman test	30.35	0.00

A *p*-value less than 0.1 indicates significance at the 10% level; a *p*-value less than 0.05 indicates significance at the 5% level; and a *p*-value less than 0.01 indicates significance at the 1% level. All variables in the table are statistically significant.

4.3 Analysis of baseline regression results

This study employs the Spatial Durbin Model (SDM) to identify the key factors influencing carbon emissions per unit of beef in China's beef cattle industry. The regression results are analyzed using three different spatial weight matrices: the adjacency matrix, the geographic distance matrix, and the spatial economic-geographical nested matrix. The regression coefficients and their significance levels are shown (Table 7), and the following section provides an in-depth analysis of the results based on these matrices. Firstly, environmental governance consistently demonstrates a significant negative impact across all three matrices, indicating that strengthening environmental governance is essential for reducing carbon emissions per unit of beef. The regression coefficients for environmental governance are −0.012, −0.013, and −0.014 in the adjacency matrix, geographic distance matrix, and

TABLE 7 Regression results analysis of the Spatial Durbin Model.

Variable	Adjacency matrix		Geographic distance matrix		Spatial economic-geographic nested matrix	
	Coefficient	Standard error	Coefficient	Standard error	Coefficient	Standard error
Envi	−0.012***	0.003	−0.013***	0.003	−0.014***	0.003
Econ	−0.003	0.002	−0.006**	0.002	−0.001	0.002
Invest	0.295***	0.075	0.241***	0.069	0.228***	0.072
Mech	−0.001	0.001	0.000	0.001	−0.003***	0.001
Scale	121.330***	37.732	62.919*	33.053	74.264**	33.067
Educ	−4.970***	0.976	−4.229***	0.977	−4.186***	0.983
Consu	0.113	0.213	−0.151	0.219	−0.248	0.222
Inco	8.338***	1.594	6.285***	1.589	4.233**	1.473
Tech	2.105	2.054	−2.013	2.126	1.091	1.934

*, **, *** denote statistical significance at the 10%, 5%, and 1% levels, respectively.

spatial economic-geographical nested matrix, respectively, all of which are statistically significant at the 1% level. This suggests that improving environmental governance not only enhances resource utilization efficiency but also helps reduce carbon emissions, regardless of geographical or economic proximity.

The effect of economic development level varies across the matrices. In the adjacency matrix, the regression coefficient is −0.003, which is not statistically significant, suggesting that the direct impact of economic development on carbon emissions is minimal. However, in the geographic distance matrix, economic development level is negatively correlated with carbon emissions, and this effect is significant. In the spatial economic-geographical nested matrix, however, the relationship is not statistically significant. These findings imply that more economically developed regions may adopt green technologies and low-carbon farming practices earlier, thus reducing carbon emissions, but the influence of this effect varies across regions. Research investment (invest) consistently shows a significant positive relationship with carbon emissions in all three matrices. Whether using the adjacency matrix, the geographic distance matrix, or the spatial economic-geographical nested matrix, research investment remains significantly positive at the 1% level. While increased research investment can drive technological advancements, it may not immediately result in carbon reduction technologies or management practices. This delay can be attributed to the time required to effectively apply research outcomes and to the pace at which new technologies are implemented.

The degree of scale exhibits a strong positive relationship with carbon emissions in the adjacency matrix, where the regression coefficient is 121.330, indicating a highly significant association. This suggests that larger-scale farming operations may lead to increased carbon emissions, possibly due to the insufficient application of environmental protection technologies. Although large-scale farming can improve production efficiency, it may also result in higher carbon emissions and resource waste if green technologies are not fully integrated. Education level consistently shows a significant negative impact on carbon emissions, with regression coefficients of −4.970, −4.229, and −4.186 across the three matrices, all statistically significant. These results imply that higher education levels promote greater environmental awareness, which in turn encourages the adoption of low-carbon technologies, leading to a reduction in carbon emissions. The urban–rural income gap is positively associated with carbon emissions, with regression coefficients of 8.338, 6.285, and 4.233. This suggests that regions with larger income disparities tend to have higher carbon emissions, likely due to lower production efficiency and less sustainable consumption patterns in these areas. Mechanization level shows a significant negative impact only in the spatial economic-geographical nested matrix, with no significant effects observed in the other two matrices. Increased mechanization can enhance production efficiency and reduce energy consumption, but the benefits may not be fully realized in certain regions where technological upgrades are incomplete.

Technological level does not show a significant effect on carbon emissions in any of the three regression models. This suggests that, within the scope of the study, technological advancements have not yet translated into substantial reductions in carbon emissions, possibly because some regions have not yet fully implemented low-carbon technologies. In conclusion, environmental governance and education levels have a significant negative impact on carbon emissions per unit of beef, highlighting the importance of environmental policies and educational investments in reducing carbon emissions. On the other hand, factors such as research investment, scale, and the urban–rural income gap present more complex relationships, which require further exploration of their mechanisms in different regions and production models. From a spatial perspective, the regression results from the three matrices reveal spatial dependencies in regional carbon emissions, suggesting that green development levels in different areas are influenced by geographic distance, economic ties, and other spatial factors. As such, policy development should take these regional differences into account, tailoring emission reduction strategies to local conditions.

4.4 Analysis of spatial spillover effects

Building upon the regression analysis using the Spatial Durbin Model (SDM), this study further investigates the spatial spillover effects of various variables. The results reveal that environmental governance has significant negative spillover effects in both the

TABLE 8 Analysis of spatial spillover effect results.

Variable	Adjacency matrix	Geographic distance matrix	Spatial economic-geographical nested matrix
Envi	−0.005 (−1.20)	−0.063*** (−3.14)	−0.059*** (−3.17)
Econ	0.024*** −5.59	0.012 (−0.81)	0.026*** (−2.69)
Invest	−0.167 (−1.24)	−0.052 (−0.08)	−0.717* (−1.73)
Mech	−0.015*** (−7.14)	−0.018** (−2.53)	−0.014*** (−2.81)
Scale	−148.969** (−2.03)	−297.010 (−1.46)	−76.501 (−0.45)
Educ	7.755*** −3.44	9.472 (−1.10)	−5.347 (−0.83)
Consu	2.862*** −5.46	−10.512*** (−3.95)	−3.375** (−2.24)
Inco	1.562 −0.55	47.563*** (−5.82)	41.541*** (−5.29)
Tech	−2.611 (−0.59)	−27.265* (−1.66)	3.513 (−0.30)

*, **, *** denote statistical significance at the 10%, 5%, and 1% levels, respectively. Values in parentheses represent Z-values.

geographic distance matrix and the spatial economic-geographical nested matrix (Table 8). This finding suggests that effective environmental governance not only reduces carbon emissions within the local area but also contributes to the reduction of carbon emissions in neighboring regions through cross-regional policy coordination (Xu et al., 2022).

The economic development level exhibits a significant positive spillover effect in both the adjacency matrix and the spatial economic-geographical nested matrix. This suggests that economic growth not only drives local low-carbon development but also enhances carbon reduction efficiency in neighboring regions through economic linkages. However, in the geographic distance matrix, the spillover effect of economic development is not significant, indicating that the impact of economic growth on neighboring areas may vary depending on spatial relationships (Chen et al., 2020; Ayyildiz and Erdal, 2021). Research investment, on the other hand, shows a negative spillover effect in the spatial economic-geographical nested matrix. This suggests that the concentration of research resources in specific regions may hinder the diffusion of benefits to adjacent areas in the short term, possibly due to limited dissemination of research advances and the slow adoption of effective carbon reduction technologies across regions.

The mechanization level consistently shows significant negative spillover effects across all matrices, suggesting that increased mechanization reduces carbon emissions in neighboring regions by enhancing production efficiency and lowering energy consumption. The degree of scale and education level, however, exhibit distinct spillover effects under the adjacency matrix. The spillover effect of scale is negative, indicating that large-scale farming primarily reduces carbon emissions in adjacent regions. In contrast, the spillover effect of education is positive, suggesting that higher education levels in one region can lead to increased carbon emissions in neighboring areas through labor mobility and the diffusion of knowledge. Per capita beef consumption demonstrates a positive spillover effect in the adjacency matrix, implying that increased consumption demand drives production and consumption in neighboring regions. However, in more distant areas, it shows a negative spillover effect, likely due to resource competition that limits the carbon reduction benefits.

Overall, environmental governance, economic development, and mechanization levels demonstrate significant spillover effects, emphasizing their cross-regional influence. In contrast, research investment, scale of production, and education levels tend to have a more localized impact. Policymakers should take these disparities into account by promoting regional collaborative governance and optimizing resource allocation to effectively advance low-carbon development goals (Xiong et al., 2022; Hang et al., 2024).

5 Conclusion and recommendations

This study employs panel data from 31 provinces in China, covering the period from 2009 to 2022, to estimate the carbon emissions of the beef cattle industry and identify the factors influencing these emissions. The findings yield several key conclusions. Firstly, between 2009 and 2022, carbon emissions from China's beef cattle industry demonstrated an overall declining trend, with particularly notable reductions in the eastern and central regions. These declines were largely driven by the widespread adoption of intensive farming practices and the dissemination of green emission-reduction technologies. Nevertheless, methane emissions from beef cattle gastrointestinal fermentation and manure management remain the primary sources of carbon emissions, and are closely linked to the expansion of farming scales. Secondly, spatial analysis reveals a pronounced spatial clustering effect in the carbon emissions per unit of beef across China. The factors influencing carbon emissions predominantly include environmental governance, economic development level, and degree of mechanization. Notably, environmental governance has a significant positive impact on reducing carbon emissions. While research investment and scale farming have enhanced production efficiency, they have not effectively reduced carbon emissions in the short term and may even have adverse effects. Additionally, education levels and urban–rural income disparities significantly influence carbon emissions, with higher education levels fostering low-carbon development.

Based on these findings, the study proposes the following policy recommendations. Firstly, it is essential to dismantle regional barriers and establish collaborative regional emission reduction mechanisms. Given the significant spillover effects of carbon emissions in the beef cattle industry, emission reduction measures confined to individual regions may fail to achieve the desired outcomes. Therefore, promoting cross-regional collaborative governance, sharing emission reduction experiences and technologies, and fostering synergies are crucial to amplify emission reduction benefits. Secondly, attention should be directed towards the innovation and dissemination of low-carbon technologies to accelerate the green transformation of the industry. Technological innovations, especially in areas such as feed optimization, manure management, and energy efficiency, hold the potential to significantly reduce carbon emissions. As such, the government should enhance funding support and policy guidance for the research and development of low-carbon technologies. By leveraging tax incentives, financial subsidies, and other policy tools, the rapid adoption and application of green production technologies can be ensured, facilitating their swift transition into productive capacities. In the future, systematic research on the low-carbon development of the beef cattle industry should focus on integrated innovations across the entire industrial chain. Key areas include: biotechnological approaches such as precision nutritional regulation and genetic improvement; optimization of manure recycling and waste resource utilization systems; development of intelligent carbon footprint monitoring technologies; and ecological regulation mechanisms for integrated crop-livestock systems. Furthermore, future research should aim to couple policy tool innovation with the localization of international best practices, addressing the practical challenges of translating advanced technologies into scalable industrial applications. Priority should also be given to overcoming bottlenecks in key low-carbon technologies and to advancing techno-economic feasibility studies through interdisciplinary research, thereby facilitating the sustainable transformation of the industry.

Furthermore, advancing integrated crop-livestock systems offers a promising pathway for achieving carbon emission reductions by enhancing resource recycling and promoting low-carbon agricultural practices. By rationally utilizing agricultural by-products as livestock feed, dependence on external feed sources can be minimized, thereby reducing carbon emissions and improving the efficiency of resource utilization. In this context, promoting the development of integrated crop-livestock systems is essential. This involves designing region-specific farming models and emission reduction strategies that take into account the diverse natural resource conditions across different areas. Such strategies will not only contribute to reducing carbon emissions within the beef cattle industry but also play a pivotal role in advancing China's agricultural sector toward a low-carbon, green, and sustainable transformation. In turn, these efforts will provide crucial support in meeting China's "Dual Carbon" goals—carbon peaking and carbon neutrality—by fostering a more sustainable agricultural landscape. Therefore, promoting the development of integrated crop-livestock systems is critical for optimizing resource use and reducing carbon emissions in the beef cattle industry. By tailoring farming models and emission reduction strategies to the specific natural resource conditions of each region, it becomes possible to enhance both environmental sustainability and agricultural productivity. Such integrated systems not only facilitate significant reductions in carbon emissions but also contribute to the broader transformation of China's agriculture towards a low-carbon, green, and sustainable future. This approach plays a pivotal role in advancing China's agricultural sector towards achieving the "Dual Carbon" goals of carbon peaking and carbon neutrality, offering essential support for national and global sustainability objectives.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

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

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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The author(s) declare that no Gen AI was used in the creation of this manuscript.

Publisher's note

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Appendix

TABLE A1 Emission factors for carbon accounting in the beef cattle industry.

Industry chain stage	Emission source	Emission factor	Value	Unit	Reference
Upstream cultivation stage	Feed crop cultivation	CO_2-equivalent emission factor of corn	1.50	t/t	Tian and Yin (2022)
	Feed transportation and processing	CO_2-equivalent emission factor of corn	0.0102	t/t	Food and Agriculture Organization (FAO) (2006)
		CO_2-equivalent Emission factor of soybean	0.1013	t/t	
		CO_2-equivalent emission factor of wheat	0.0319	t/t	
Midstream farming stage	Enteric fermentation of beef cattle	CH_4 emission factor	54	kg/head·year	IPCC (2019)
	Manure management system	CH_4 emission factor	2.823	kg/head·year	Department of Climate Change, NDRC (2011)
		N_2O emission factor	0.7657	kg/head·year	Department of Climate Change, NDRC (2011)
	Energy consumption in beef cattle farming	Unit price of electricity for beef cattle breeding	0.4275	Yuan/KWh	Meng et al. (2014)
		CO_2 emission factor of electricity consumption	0.9734	t/MWh	
		Coal unit expenditure for beef cattle breeding	800.00	Yuan/t	Sun et al. (2010)
		Coal consumption CO_2 emission coefficient	1.98	t/t	
Downstream processing stage	Beef product processing	Beef product processing energy consumption coefficient	4.37	KJ/kg	Meng et al. (2014)
		One degree electric calorific value	3.60	MJ/KWh	

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Is climate neutral possible for the U.S. beef and dairy sectors?

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The objective of this review and modeling effort is to define climate neutrality as it relates to beef and dairy production, and to introduce accounting methods that will help guide the livestock industry's ability to achieve climate targets, to summarize emission mitigation strategies, and present potential scenarios to achieve climate neutral emissions for the beef and dairy industries. The global target to limit global warming to 1.5°C above pre-industrial levels by 2050 has resulted in many companies, including agribusiness companies, setting voluntary emission reduction targets. The main concept behind these goals is that GHG emissions do not exceed the GHG removed from the atmosphere by GHG sinks. Where multiple greenhouse gases are involved, the quantification of climate neutral emissions depends on the climate metric and time horizon chosen to place these gases on an equivalent basis (e.g., global warming potential, and global warming potential-star). As the ruminant supply chain emits both short-lived (methane; CH_4) and long-lived (carbon dioxide and nitrous oxide) GHGs, how companies choose to account for these gases will impact their progress toward these goals. Further, mitigation strategies for beef and dairy systems have predominantly focused on enteric CH_4 emissions and soil C sequestration. However, several hurdles still exist to reduce emissions by the magnitude required to realistically achieve a net zero supply chain. Determining the ability of a system to be climate neutral is a complicated and complex process and will not be achieved by a "silver bullet" approach. The scientific community will need to develop multiple mitigation strategies that are regionally and contextually adaptable.

KEYWORDS
climate neutrality, manure emissions, enteric emissions, ruminant livestock, greenhouse gas emissions

1 Introduction

As the climate change crisis becomes more pressing, the call for companies and individuals to act has intensified. Atmospheric carbon dioxide (CO_2) levels have been rising rapidly since the start of the industrial revolution and were higher in 2019 than any time in the last 2 million years (IPCC, 2021). In a recent re-analysis of climate change over the last 24,000 years, Osman et al. (2021) reported that the current rate and change of global temperature is unprecedented. They indicated in the last 200 years there was an approximate 2°C increase in global mean surface temperature, which is a 180 times greater rate of change compared to the 0.5°C increase in global mean surface temperature increase from the 9,000 years prior (Osman et al., 2021). There is little uncertainty that human influence (i.e., anthropogenic emissions) is a primary driver of this change, and that continued impact is projected as global fossil fuel use continues to rise (IPCC, 2021). Increased atmospheric greenhouse gas (GHG) concentration has resulted in increased global mean surface temperature, greater variability in temperature and precipitation extremes and more frequent adverse weather events (IPCC, 2021; USGCRP, 2018). This trajectory led to the ratification of the Paris Climate Accord, which originally set a temperature target of a maximum 2.0°C rise in global average temperature—relative to a pre-industrial revolution baseline—and a more aggressive target of a maximum 1.5°C rise by 2,100 (UNFCCC, 2015). Further targets have been set since the ratification of the Paris Climate Accord, including the Global Methane pledge which aims to reduce global methane emissions by at least 30% by 2030, relative to a 2020 baseline. Such targets have major ramifications for livestock production, as enteric CH_4 emissions represent 5% of global anthropogenic GHG emissions and 27% of anthropogenic CH_4 emissions according to the IPCC sixth assessment report (Dhakal et al., 2023).

Historically, considerable effort has been directed at improving production efficiency. Resulting from this increased production efficiency, the carbon footprint (i.e., GHG emissions per unit of product) have been reduced substantially (Beauchemin et al., 2020). However, while improved efficiency is beneficial, a reduction in absolute emissions must occur to prevent further climate change, especially to achieve the targets set by the Paris Climate Accord and other climate pledges. These pledges necessitate a quantitative limit on the amount of CO_2 that can be emitted, requiring all sectors—regardless of relative contribution – to reduce their emissions to meet the goals (Rogelj et al., 2016). In the United States during 2022, the agriculture sector was responsible for 9.4% of all GHG, while transportation was responsible for 28.4%, electricity generation was responsible for 25%, and industry (cement, iron, steel, aluminum, etc.) was responsible for 23% (EPA, 2024). The only two sectors emitting fewer GHG emissions in 2022 than agriculture were the commercial (7.3%) and residential (6.2%) sectors (EPA, 2024). In 2022, agricultural soil management accounted for 49% and enteric methane (CH_4) accounted for 32.5% of U.S. agricultural GHG emissions, indicating priority focus should be given to reducing emissions from these sources (EPA, 2024). Beef and dairy enteric CH_4 represented 2.2% and 0.8% of all GHG emissions in the US in 2024, respectively (EPA, 2024). Despite contributing a relatively small portion of the United States' emissions, animal agriculture must reduce emissions to meet the previously mentioned climate pledges such as that of the global methane pledge.

Outside of inter-governmental agreements, many food and agriculture companies have made commitments to reduce GHG emissions and increase offsets to reduce their contribution to climate change. Beef and dairy supply-chain and producer organizations in the U.S. have begun to make "net zero" or "climate neutral" or similar commitments. What these specific commitments mean, and their implications will be discussed in detail in later sections. These goals, while laudable, will require considerable economic investment, producer buy-in and scientific research to aid policy makers and stakeholders in developing roadmaps toward achieving such goals. However, no clear roadmap "net zero" or "climate neutral" currently exists and organizational climate goal definitions can be inconsistent. Therefore, the purpose of this review is to set the table for achieving climate goals by drawing from scientific literature, special reports, and white papers to define net zero and climate neutral, outlining current mitigation strategies, and discussing potential pathways for the U.S. beef and dairy industry to achieve net zero.

2 Emission changes over time

Agriculture is a direct contributor of GHG emissions, with CH_4, nitrous oxide (N_2O), and CO_2 being the primary GHG produced (EPA, 2024; Figures 1, 2). In 2022, the U.S. agriculture sector produced a total of 8,595 kt of CO_2, 9,885 kt of CH_4, and 1,162 kt of N_2O (EPA, 2024). Greenhouse gas emissions can be considered in absolute emissions amounts, such as kt of the specific gas emitted as presented in the prior sentence, or in amounts of carbon dioxide equivalents (CO_2-e). Carbon dioxide equivalents allow for comparison of the radiative forcing ability of different gases and equate it to the radiative forcing ability of CO_2 (termed the global warming potential; GWP). As such, CO_2 always has a CO_2-e of 1, and for GWP on a 100-year time-horizon (GWP100), CH_4 and N_2O have CO_2-e of 28–36 and 265–298, respectively (IPCC, 2021). Therefore, the U.S. agriculture sector emitted 593.4 MMT of CO_2-e from CO_2, CH_4, and N_2O. This represents approximately 9.4% of total U.S. GHG emissions (EPA, 2024).

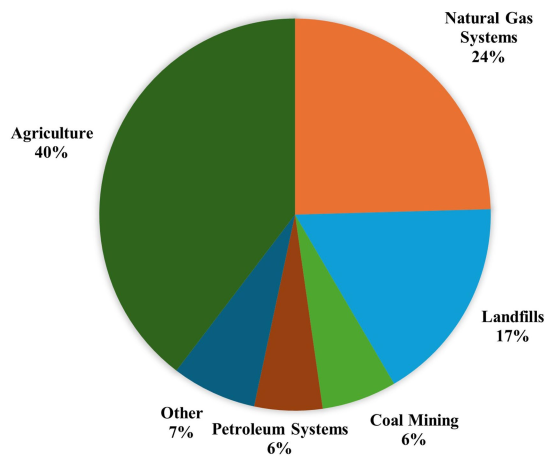

FIGURE 1
U.S. CH_4 emissions by Source, 2022 (percent of MMT CO_2eq.) adapted from EPA (2024).

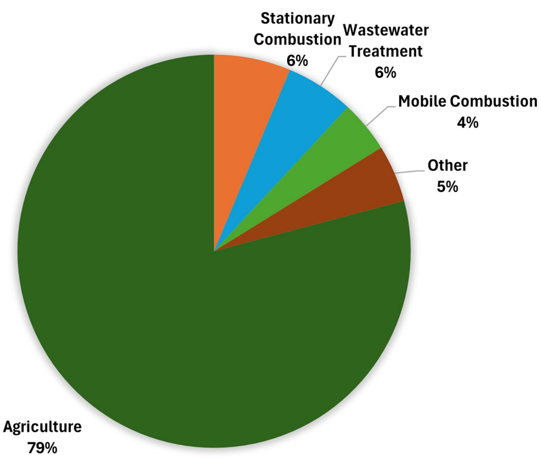

FIGURE 2
U.S. N_2O emissions by Source, 2022 (percent of MMT CO_2eq.) adapted from EPA (2024).

Since 1970, there has been a 1.4-fold increase in the global number of cattle, buffalo, sheep, and goats, which is closely linked to trends in reported CH_4 emissions from enteric fermentation of ruminants (Beck et al., 2023a; IPCC, 2014). However, for achieving net zero, global statistics do not provide insight into place-specific emissions profiles, causes for those emissions, and options for mitigation. As such, it is important to consider U.S. specific trends. From 1990 to 2022, GHG from U.S. agriculture has increased by 7.2%, due to increased demand for food products from growing populations, increase in N_2O emissions from management of soils, and increased CH_4 and N_2O emissions from manure management systems (EPA, 2024). Emissions from enteric fermentation have also increased by 5% from 1990 to 2022 (EPA, 2024). However, while absolute emissions have increased, emissions per unit of product produced have been decreasing which indicates increased efficiency of production of animal products (EPA, 2024; Crawford et al., 2022; Capper et al., 2009).

Historically, wild ruminant populations—specifically Bison—may have been large enough that their methane emissions were near the current emissions from livestock until their extermination in the mid-1800s (Hristov, 2012; Kelliher and Clark, 2009). To date, minimal research has examined emissions of wild ruminant herds or historic populations, but wild ruminants have always inhabited North America and how this may help contextualize emissions from contemporary livestock production, which has since replaced wild ruminants (Hristov, 2012). Hristov (2012) estimated the historic enteric methane emissions from wild ruminants in the U.S. and compared them to present day farmed ruminants and reported emissions were approximately 86% of today's emissions when the bison population was estimated to be 50 million. Similarly, Kelliher and Clark (2009) used IPCC tier 2 methodology to estimate emissions from the historic Northern Great Plains bison and compared them to today's farmed ruminants across the same landscape. They reported the historic herd produced 2.2 MMT/CH_4 $yr.^{-1}$ compared to 2.5 MMT/CH_4 $yr.^{-1}$ from today's ruminants. Smith et al. (2015) investigated the historical extirpation or reduction of large herbivores including that of the American bison and the subsequent biogeochemical effects of these events. The authors found that while the emission reduction from this event was not as significant as others from the historical record, their estimate was like Kelliher and Clark (2009) with a reduction of 2.2 MMT/CH_4 $yr.^{-1}$. While these studies provide an example of the magnitude of emissions that may have arisen from wild ruminants, more work is needed to understand how these historic populations influenced short-term temperature change. Such research would help contextualize how alterations in modern emissions rates from the beef and dairy sectors may impact global temperatures. Additionally, many of the animals today are fed in confinement operations, and therefore have different impacts with the surrounding ecosystems (e.g., water quality, air quality, etc.) than historic herbivores.

Recent data shows that the beef and dairy sectors have succeeded in reducing environmental impacts per unit of product produced compared to historical estimates (Crawford et al., 2022; Capper and Cady, 2019; Capper, 2011; Capper et al., 2009). Over time, animal agriculture has increased its efficiency by producing more products with less resources, resulting in a lower GHG emissions footprint per unit of product (Rotz et al., 2021; Capper, 2011; Capper et al., 2009). In a comparative analysis of the U.S. dairy industry, emission estimates from 1944 to 2007 were compared and it was found that the environmental impact of milk production was overall reduced by 37%, with a 64% reduction in dairy cattle population and a 57% reduction in CH_4 per unit of product produced (referred to as emission intensity—GHG per unit of product produced; Capper et al., 2009). Advances in dairy cattle nutrition, genetics, management, and health have led to greater efficiency and productivity (Capper and Cady, 2019). Through this, U.S. dairy can produce more milk, with fewer resources, meaning fewer animals requiring less feedstuffs, less water, and less land (Capper et al., 2009). In dairy systems, total manure output has also decreased by 20.6% from 1944 to 2007 (Capper and Cady, 2019). This results in lower CH_4 and N_2O emissions from manure and manure storage. Furthermore, Cole and Van Raden (2011) reported that there is still genetic potential for improvements in milk yield and milk production does not appear to be approaching a biological maximum.

Similarly, the U.S. beef industry has seen improvements between historic and modern emission intensity estimates (Capper, 2011). In 2007, beef production systems produced 81.9% of the manure, 82.3% of the CH_4, and 88.0% of N_2O per beef produced relative to 1977 (Capper, 2011). Additionally, it required only 69.9% of the animals, 67% of the land and reduced the C footprint by 16.3% relative to 1977. In a more recent comparative analysis, Crawford et al. (2022) compared the carbon footprint of finishing cattle during 1990 and 2020. They reported that in 2020 the carbon footprint was 4.4% lower, with 47.5% more body weight gain, and 1.4% less cattle relative to 1990. However, absolute emissions in CO_2-e were increased by 39.5% over this period. This increase in absolute GHG emissions by the feedlot sector was due in part to an increased number of days on feed and subsequent increasing dry matter intake. The authors argue that by increasing days spent in the feedlot and decreasing days spent in the cow-calf and stocker sectors should decrease the overall carbon footprint of the beef industry (Crawford et al., 2022). This agreed with Stackhouse-Lawson et al. (2012) who reported that if the stocker sector was removed, absolute emissions in CO_2-e may be reduced by 6.5% in California. However, increasing reliance on diets high in starch would reduce the advantage that ruminant species have in converting complex carbohydrates and untillable land into human-edible protein (Carvalho et al., 2018). Further, this would require an increase in feed production from cropping systems, which is already a challenge in many regions due to drought and shrinking aquifer levels.

It is important to consider the difference between absolute emissions and emission intensity and their implications for climate related pledges made by governments and companies. Emission intensity is the GHG emitted per unit of product, whereas absolute emissions are the total emissions of a production system. Both absolute emissions and emission intensities need to be reduced to meet climate goals while also balancing other complex issues like global food supply, rural livelihoods, and cultural values. To meet the growing population's demand for food products, agriculture will have to continue to increase production. If the necessary decreases in emissions intensity occur at a similar rate to the needed increase in production, the absolute emissions will remain constant (Ungerfeld et al., 2022). If absolute emissions remain constant, the set climate goals will not be met. As such, improving animal productivity and emissions intensity is not enough to achieve the necessary reductions in absolute emissions (Ungerfeld et al., 2022). Historically, animal agriculture has been producing more products more efficiently through reducing emissions intensity, but has increased absolute emissions (Crawford et al., 2022). Therefore, there are still considerable improvements that need to occur to reduce both emissions intensity and absolute emissions if the industry is going to meet its climate goals as described in the following section.

3 What is net zero and climate neutral?

There are numerous terms used in the sustainability space to describe climate goals (Table 1). Net zero, net zero carbon, net zero emissions, climate neutrality, and carbon neutrality are all interrelated terms that have slightly differing definitions and implications. The main concept behind these goals is that GHG emissions (of one or many gases) from sources do not exceed the GHG removed from the atmosphere by sinks. However, different stakeholders may choose to use one term over another to be more specific or highlight a difference in their specific goals toward lower impact production.

All organizations have a balance between their positive and negative impacts on the environment, and their actions to counteract any negative externalities. This balance is either net negative, net zero, or net positive. In other words, overall impacts and counteractions will result in either an overall negative impact on the environment (net negative), an overall positive impact on the environment (net positive), or overall no impact on the environment (net zero).

According to the EPA (2021), net zero and net positive strategies are long-term solutions for sustainability and help build resilience by meeting environmental objectives. These strategies represent sustainability in action (EPA, 2021), although we have yet to see how the public and political systems will react to an organization's failure to achieve climate benchmarks due to the long-time horizon companies have given themselves to achieve their commitments. The EPA focuses net zero and net positive strategies on water, energy, and waste. However, many organizations only focus on net zero GHG emissions, whether that be net zero emissions or net zero carbon. Of note, some company commitments are not transparent in what their target is (i.e., absolute vs. emission intensity) or what plans are in place to achieve these emissions. Additionally, in the future, it may be important to expand past emission goals and consider water, energy, and waste goals as well.

Net zero can be broken down further into net zero emissions (all GHG) and net zero carbon (CO_2). Net zero emissions were defined by the IPCC (2018) as: when anthropogenic emissions of greenhouse gases to the atmosphere are balanced by anthropogenic removals over a specified time. Net zero emissions including all greenhouse gas (GHG) emissions adds complexity to accounting and determining net zero.

Net zero carbon also known as net zero CO_2 emissions or carbon neutrality were defined by the IPCC (2018) as: when anthropogenic CO_2 emissions are balanced by anthropogenic CO_2 removals over a specified time. The IPCC (2021) states that achieving global net zero CO_2 emissions is necessary to stabilize the CO_2-induced global climate change.

Climate neutrality was defined by the IPCC (2018) as a state in which human activities result in no net effect on the climate system. Achieving climate neutrality would require reducing emissions and balancing any remaining emissions with emission removal (IPCC, 2018).

3.1 Goals of industry

Numerous net zero and climate neutrality commitments have been made by countries, private sector companies, as well as producer organizations along the agriculture/food system value chain (Ungerfeld et al., 2022). For example, the National Cattlemen's Beef Association has set a goal to "demonstrate the climate neutrality of U.S. cattle production by 2040" and U.S. Dairy has created an initiative to "achieve GHG neutrality" by 2050 (NCBA, 2021; U.S. Dairy, 2020). As seen in Table 2 commitments differ greatly among different companies and organizations, varying in terms used, definitions, baseline year, and goal year. This choice of terminology can reflect vastly different outcomes and can lead to confusion for stakeholders. For example, the original commitment made by the Innovation Center for U.S. Dairy was to achieve carbon neutrality (U.S. Dairy, 2020), which is now changed to GHG neutrality (U.S. Dairy, 2023). According to the IPCC definitions, the original goal would have been only focused on anthropogenic CO_2 emissions, but not inclusive of CH_4 which is the primary GHG from the dairy industry. However, their updated choice of terms is now inclusive of all GHG emissions. With respect to the U.S. supply chain, most organizations have aligned internal commitments with those of the producer organizations. The chosen term and definition for a net zero or climate neutrality goal, as well as the scope, and the accounting metrics utilized to determine both baseline and progress, greatly impacts the ability of any stakeholder to achieve a set goal. Globally, Seneviratne et al. (2021) states with high confidence that reaching and sustaining global net zero CO_2 emissions and reducing non-CO_2 emissions radiative forcing would halt human-caused climate change. As such, achieving net zero

TABLE 1 IPCC (2018) definitions related to climate goals.

Term	Definition
Climate change commitment	the unavoidable future climate change resulting from inertia in the geophysical and socio-economic systems. It is usually quantified in terms of the further change in temperature, but can include other future changes.
Climate neutrality	the concept of a state in which human activities result in no net effect on the climate system. Achieving such a state would require balancing of residual emissions with emission (carbon dioxide) removal.
Net negative emissions	a situation of net negative emissions is achieved when, as result of human activities, more greenhouse gases are removed from the atmosphere than are emitted into it.
Net zero carbon dioxide (CO_2) emissions	achieved when anthropogenic CO_2 emissions are balanced globally by anthropogenic CO_2 removals over a specified period. Net zero CO_2 emissions are also referred to as carbon neutrality, net zero carbon dioxide, and carbon neutrality.
Net zero emissions	achieved when anthropogenic emissions of greenhouse gases to the atmosphere are balanced by anthropogenic removals over a specified period.

CO_2 emissions is required and should be included in all net zero and climate neutral goals. This indicates for many non-agriculture companies that current work toward net zero should focus heavily on CO_2 emissions being at least equal to CO_2 sequestration and offsets, and then toward mitigating non-CO_2 emissions. However, for ruminant livestock this would obviously not hold true due to the predominate emission source being enteric CH_4 production.

While not reflected in Table 2 many of the food and beverage company commitments have variable intermediate targets set to benchmark and, ultimately, achieve their larger, more ambitious targets. These intermediate targets are typically differentiated by scope, i.e., Scope 1 (direct emissions from operations), Scope 2 (indirect emissions from company activities but not controlled by the company), and Scope 3 (indirect emissions related to their products) (WRI and WBCSD, 2004). For agriculture companies, the largest source of emissions, typically, comes from scope 3 emission sources. That is, emissions that arise in the rearing and production of livestock animals, which is often greater than 50% of the company GHG emissions, although not every company reports these emissions directly due to the complexity of a global food supply chain and product sourcing (JBS, 2023; Tyson, 2023). This has manifested a new reality for the beef and dairy supply chain, in that these company commitments alongside global markets will shape livestock production methods for the producers within their supply chains (Leahy et al., 2020), and will likely increase the need for traceability of products and animals.

4 Accounting metrics

Carbon dioxide, CH_4 and N_2O are the predominant contributing GHG to global climate change and beef and dairy systems are important contributors of CH_4 and N_2O. For accounting of climate impacts between companies, industries, etc., it is necessary to relate different GHG to an equivalent basis. Typically, non-CO_2 emissions are reported using GWP100 with CO_2 as the reference gas. As the reference gas CO_2 has a GWP100 of 1, CH_4 has a GWP100 of 28–36, and N_2O has a GWP100 of 265–298 (IPCC, 2021). By using a static weighting factor based on the radiative forcing of different gases over the selected time horizon, the GWP100 approach implements a simplified means to relate different GHG to an equivalent basis. While providing consistent reporting, this type of metric has inherent flaws due to the differing dynamics of these gases in the atmosphere (Lynch et al., 2021). The use of the GWP100 metric, while the standard for several decades, has long been debated due to its inability to accurately capture the atmospheric behavior of, particularly, short-lived climate forcers (SLCF), also referred to as flow gases (O'Neill, 2000; Fuglestvedt et al., 2003; Shine et al., 2005, 2007). Methane is one such SLCF and has an atmospheric residence time of about 12 years, while N_2O, the second predominant GHG relevant to beef and dairy production, has a residence time of approximately 114 years (EPA, 2024). Carbon dioxide is a stock gas and has an atmospheric residence time of over 1,000 years. As such, the relationship between cumulative CO_2 emissions and CO_2-induced warming is near linear (Cain et al., 2021). This relationship does not hold true for the cumulative warming effects of CH_4 due to its short-lived behavior in the atmosphere (Smith et al., 2012). For N_2O emissions, however, the atmospheric half-life is long enough that traditional GWP100 accounting may sufficiently model its impact as public policy is typically set for the years 2050 or 2100 (Lynch et al., 2021).

As GWP100 incorrectly accounts for the warming potentials of short-lived GHGs, there has been a long history of alternative metrics that have been developed including global temperature potential (GTP; Shine et al., 2005). This climate metric sought to improve upon

TABLE 2 Current company climate commitments.

Company	Goal^	Baseline year
ADM	Reduce GHG by 25% by 2035	2019*
Cargill	Reduce GHG per ton of product sold by 30% by 2030	2017
Innovation Center for U.S. Dairy	GHG Neutral by 2050 for U.S. Dairy Industry	-
Coca-Cola	Reduce emissions of greenhouse gases 25% by 2030	2015
Danone	Net Zero emissions by 2050	-
General Mills Inc.	Net zero by 2050	2020
JBS USA	Net Zero by 2040	2021*
Kellogg Co.	Reduce GHG from suppliers by 50% by 2050	2015
McDonalds	Net zero emissions by 2050	2015
Nestle	Carbon Neutral by 2050	2018
PepsiCo, Inc.	Net zero by 2040	2015
Smithfield Foods	Carbon negative by 2030	-
Tyson Foods	Net zero by 2050	2016
Unilever	Net zero emissions by 2039	2015*
National Cattlemen's Beef Association	Demonstrate climate neutrality by 2040	-
Walmart	Net zero emissions by 2040	2015
Yum Brands	Net zero by 2050	2019

^Company websites. *Variable Baseline year depending on scope 1, 2, or 3 emission source for intermediate targets.

the known issues of GWP, and is calculated as the ratio of a gases absolute GTP to that of CO_2. Absolute GTP is determined for each gases species as the global-mean temperature change at a given time horizon from a 1 kg pulse of the gas (Shine et al., 2005; Boucher et al., 2009). One newer strategy, GWP*, more accurately accounts for the warming potential of flow gases such as methane. This method utilizes emissions rates of a given year and relates them to previous emission rates, typically 20 years prior, to calculate a CO_2 warming equivalence (CO_2-we). The benefit of using a "step-pulse" metric like GWP*, is that it better captures the climate impact of methane in the short-term before it is broken down in the atmosphere without overestimating its impact in the long-term (Cain et al., 2019). This means that CH_4 has the potential to reach a sustained equilibrium where ongoing emissions can be matched by natural removals to the point that continued climate warming is not occurring and can lead to reversing warming in a few decades. This metric has been demonstrated to relate closely to actual temperature responses using the "Finite Amplitude Impulse Response" (FaIR) simple climate model, which is not achieved when using GWP100. In fact, Lynch et al. (2021) found that GWP100 overestimated climate impacts when CH_4 emissions were constant or decreasing. Therefore, flow gases should not be accounted for like stock gases (Liu et al., 2021), and success should not be measured via an abstract and highly ambiguous reporting unit whose primary virtue is customary use (GWP100) (Lynch et al., 2021).

The importance of capturing rate change, both increasing and decreasing, for CH_4 emissions was demonstrated by Beck et al. (2023b). In that paper, U.S. EPA methane emission estimates from livestock between 1990 to 2020 were re-analyzed using GWP* compared to the traditional GWP100 used by EPA (2024). Emission sources were separated by species (beef, dairy, swine, and poultry) and source (enteric or manure) and the CO_2-we were calculated from 2010 to 2020 both on a yearly basis and cumulatively. It was observed that enteric emissions were relatively constant across years, whereas manure emissions, particularly from dairy production have been increasing significantly at a rate of 0.03-MMT/year. When calculated using GWP100, enteric CH_4 was the predominate GHG source at 191-MMT CO_2-e from 2010 to 2020 with manure emissions only accounting for 62.3 MMT CO_2-e during that same time. However, when using GWP* it was observed that manure CH_4 was the larger contributor to climate warming rather than enteric CH_4 (90.8 MMT CO_2-we vs. 89.2 MMT CO_2-we, respectively). This was due to changes in manure management and population that lead to divergent rate changes between these two emissions sources which is unappreciated when solely examining emissions using GWP100. Similarly, it was observed by Beck et al. (2022) and del Prado et al. (2023) that a small, 0.32% annual reduction in CH_4 emission rates would stabilize the cattle sectors impact on climate warming and further reductions could reverse historical contributions. However, this rate change metric does mean that as emission rates increase, which is typically associated with growing animal populations, the climate warming impact would increase more than GWP100. In fact, if emission rates increase annually at a rate greater than 1.01%, GWP* would produce a larger estimate than GWP100 (Beck et al., 2022). Therefore, mitigation strategies that reduce animal performance and subsequently result in producers increasing animal numbers to maintain or increase output may not actually result in any reduction in climate impact. It should be noted, that GWP100 is still the default accounting metric for GHG, and how best to apply these other metrics is unclear. For example, at what level at which GWP* could be applied is up for debate (e.g., production systems vs. national inventory). Currently, the majority of its use has been in larger inventories which are less sensitive to short term changes that can impact the annual CO_2-we values.

5 Mitigation strategies

The following sections will highlight some promising mitigation strategies for relevant agricultural GHG's, but more depth can be found in the papers highlighted in Tables 3, 4. To date, mitigation strategies for beef and dairy systems have predominantly focused on enteric CH_4 emissions and improved soil management. However, several hurdles still exist to reduce emissions by a large enough magnitude to realistically achieve a net zero supply chain.

For enteric emissions, two additives have been identified that achieve greater than 20% reductions in emission and one that supplies at least 10%: (1) 3-Nitrooxypropanol (3-NOP: DSM Nutritional Products Ltd., Kaiseraugst, Switzerland), (2) *Asparagopsis taxiformis* and (3) Nitrate (10% or more reductions) (Hegarty et al., 2021; Beauchemin et al., 2020). While it has previously been thought that reducing enteric CH_4 emissions would increase animal performance, these three feed additives have not demonstrated consistent improvements in this area. Furthermore, most research to date has focused on feedlot or total mixed ration (TMR) diets where these compounds are fed at a consistent rate and little is known about modes of supplementation in more extensive systems where the compounds would be "pulse" fed (Beck et al., 2023b; Hegarty et al., 2021). These research gaps must be addressed in the future if net zero is to be achieved as most emissions, particularly in the beef industry, occur from grazing animals (Rotz et al., 2019; Alemu et al., 2017). The magnitude of emission reductions are such that a 30% reduction in enteric CH_4 from pastoral systems would offset over 200% of feedlot produced enteric CH_4 and 74% of dairy produced enteric CH_4 (Chowdhury et al., 2024).

Regional and management variability impact the footprint of individual producers and will impact their ability to mitigate their emissions (Rotz et al., 2021; Rotz et al., 2019; Rotz et al., 2015; Stackhouse-Lawson et al., 2012). Producers must examine mitigation strategies to determine viability of adoption based on their own operation. Environmental variability to consider includes differences in soil type, local climate, and management constraints of that system (Rotz et al., 2021). Recent life cycle assessment (LCA) literature demonstrates how variable carbon footprints can be across the U.S. for beef and dairy producers due to environmental and management decisions (Rotz et al., 2019; Rotz et al., 2021; Pelletier et al., 2010; Stanley et al., 2018; Liang et al., 2017). In a National LCA on beef production broken down by geographic region, Rotz et al. (2019) reported GHG footprints ranging from a mean of 20.2 in the southwest to 28.9 kg CO_2-e./kg carcass weight in the southeastern U.S. They found areas with higher footprints were driven primarily by greater precipitation and use of fertilizers. Similarly, large variation was reported from the dairy industry by Rotz et al. (2021). Within a region variation can be quite large as well based on a particular management practice. For example, Liang et al. (2017) found that increasing soybean in the ration of Wisconsin dairy farms increased emissions per unit of energy corrected milk. However, by including soybean in the crop rotation, producers were able to reduce field N_2O

TABLE 3 Methane mitigation strategies and potentials for beef and dairy production.

Strategy	Level observed	Citation(s)
Increased animal productivity (through nutrition, genetics, health and management)	CH_4 decrease potential in g/day uncertain (can increase) CH_4 decrease potential in g/kg product is low	Beauchemin et al. (2020)
Animal breeding for low-CH_4 production	CH4 decrease potential in g/day is medium CH4 decrease potential in g/kg product is medium	Beauchemin et al. (2020) and Beauchemin et al. (2025)
Nutrition—lipids	CH4 decrease potential in g/day ~19% CH4 decrease potential in g/kg product ~12%	Arndt et al. (2022), Beauchemin et al. (2020), Beck et al. (2019), and Beck et al. (2018)
Nutrition—concentrates	CH4 decrease potential in g/day is 10%–30% CH4 decrease potential in g/kg product is 10%–20%	Beauchemin et al. (2020), Thompson et al. (2019), Knapp et al. (2014), and Hristov et al. (2013)
Nutrition—improved forage quality	CH_4 decrease potential in g/day <20% (Can increase) CH_4 decrease potential in g/kg product <20%	Thompson and Rowntree (2020), Knapp et al. (2014), and Hristov et al. (2013)
Vaccine for rumen microbiome and fermentation manipulation	CH4 decrease potential in g/day is unknown CH4 decrease potential in g/kg product is unknown	Goopy (2019) and Beauchemin et al. (2020)
Early life programming	CH_4 decrease potential in g/day is unknown CH_4 decrease potential in g/kg product is unknown	Yáñez-Ruiz et al. (2015)
3-nitrooxypropanol	CH_4 reduction of 20–40% in g/day for beef and dairy CH_4 decrease potential in g/kg product is high	Dijkstra et al. (2018), Beauchemin et al. (2020), and Yu et al. (2021)
Asparagopsis taxiformis	CH_4 reduction potential > 80% in g/day *Issues have been observed in palatability	Stefenoni et al. (2021), Roque et al. (2021), and Kinley et al. (2020)
Nitrate	CH4 decrease potential in g/day is low to medium CH4 decrease potential in g/kg product is low to medium	Beauchemin et al. (2020)
Tannins	CH_4 reduction potential 7–16% in g/day CH_4 reduction potential 8–26% per g/kg product	Arndt et al. (2022) and Hristov et al. (2013)

emissions. This finding also demonstrates that potential pollution swapping must be considered for the beef and dairy industries to achieve net zero. Pelletier et al. (2010) reported another example how different production practices can influence emissions within a given region. It was reported that cattle finished in a feedlot have smaller GHG footprints than those finished through other systems in the same region. Due to this regional complexity, local ecosystem variability, and influence of management decisions, reaching net zero for every operation may not be feasible.

Economic constraints and social impacts must be considered when designing and implementing mitigation strategies. Often, research is focused on environmental impacts, but without co-benefits that positively impact the economic viability of an operation other motivations will need to occur (Hegarty et al., 2021). These motivations could be carbon credits through offsets, legislative requirements for market access, or access to low carbon markets (Hegarty et al., 2021). An in depth discussion of individual strategies is outside of the scope of this manuscript, rather the authors encourage interested readers to utilize the citations provided. However, readers are referred to Tables 3, 4 for a synopsis of mitigation strategies and for some references to recent review and research papers.

5.1 Offsets to achieve net zero

While mitigation of emissions is necessary this will not be enough to achieve net zero. As with all livestock food products, beef and dairy production achieving zero emissions is an unrealistic goal. However, a net zero footprint may be realized through mitigation in conjunction with offsets. Agriculture could offset emissions and implement insetting programs. Insetting is where a company or system implements CO_2e emission reduction or sequestration creating programs within their system or value chain. Inset program options in animal agriculture systems include, but are not limited to, improving soil carbon sequestration, utilizing manure digesters, and implementing renewable energy generating technology.

Soil management for increased C sequestration was identified by Cusack et al. (2021) as having the largest potential to reduce beef cattle emissions globally, both per unit of product and per unit of land. This includes utilizing silvopastoral beef production, which has already resulted in niche carbon neutral beef products such as the Viva branded beef products in Brazil. This was developed through a joint effort by Marfrig Beef and the Brazilian Agriculture Research Corporation (Embrapa, 2020). In the U.S., research examining

TABLE 4 Nitrogen and carbon dioxide mitigation strategies and potentials for beef and dairy production.

Greenhouse gas	Strategy	Level observed	Citation(s)
Nitrous oxide	Application of manures to field	N_2O and CH_4 mitigation potential 0.37–1.22 t $CO_{2eq.}$ ha^{-1} $yr.^{-1}$	Eagle et al. (2011) and Herrero et al. (2016)
N_2O and NH_3	Reducing dietary protein	15%–33% reduction in volatile N loss	Erickson and Klopfenstein (2010) and Montes et al. (2013)
	Dietary tannin inclusion	17%–57% in urinary NH_3 concentration	Brandani et al. (2023)
	Timing of manure application	>30% reduction	Montes et al. (2013)
Carbon dioxide	Integrated field management for carbon sequestration	62% ± 9% reduction potential for GHG emissions per unit of beef 112% ± 39% reduction potential for GHG emissions per unit of land	Cusack et al. (2021)
	Changes in grazing management	Could lead to an annual sequestration of up to 150 $MtCO_2e$ $yr.^{-1}$ in the world's grazing lands	Herrero et al. (2016)
	Intensive rotational grazing	37 ± 7% reduction potential for GHG emissions per unit of beef	Cusack et al. (2021)
	Avoided land conversion	Climate change mitigation potential of 3,719 Tg CO_2eq per year	Cusack et al. (2021)
	Improved practices for animal productivity and health	Potential reduction of 0.2 $GtCO_2e$ $yr.^{-1}$ by 2050	Herrero et al. (2016)
All GHG	Integrated beef & dairy system	Potential reduction in carbon footprint > 50%	Tichenor et al. (2017), Stackhouse-Lawson et al. (2012), and Laca et al. (2021)

livestock-induced changes in soil C and its impact on the C footprint of beef and dairy production has been minimal (Cusack et al., 2021; Reinhart et al., 2021; Rowntree et al., 2020; Stanley et al., 2018). However, in some regions utilizing improved grazing management practices have resulted in net zero or reduced C footprints (Rowntree et al., 2020; Stanley et al., 2018) but more research is needed to understand the potential for these practices across different regions, particularly in more arid environments where soil C stocks may be at a long-term equilibrium (Derner et al., 2019; Sanderson et al., 2020). In the higher rainfall study area of Rowntree et al. (2020), a 20-year chronosequence on soil C stocks found an average sequestration rate of 2.29 Mg C ha^{-1} $yr.^{-1}$. In more arid environments, studies that have shown the potential for grazing to increase soil C is low, with rates ranging from 0.05 to 0.50 Mg C ha^{-1} $yr.^{-1}$, or may have no sequestration potential at all (Schuman et al., 2002; Henderson et al., 2015). For example, in an analysis of 74-year-old moderately grazed and grazing exclosures across a shortgrass steppe ecosystem in northeast Colorado, grazing was not found to have an impact on total soil C, rather it is hypothesized that moisture was the primary limitation in this ecosystem (Derner et al., 2019; Burke et al., 1998). In these environments, it may be more important to protect these soils from conversion into marginal cropland, as this has resulted in substantial loss of soil C (Ihori et al., 1995). This would require, however, alternative mitigation strategies if producers in these regions are going to reach net zero emissions.

For confined beef and dairy production, feed production is a significant contributor to its carbon footprint (Rotz et al., 2019; Wattiaux et al., 2019; Rotz et al., 2021). Therefore, shifting management of crop production practices to minimal or no-till, improved crop rotations, utilization of cover crops, and precision farming may result in reduced soil C losses and GHG emissions from soils (Venterea et al., 2012; Sanford et al., 2012; Wattiaux et al., 2019). In a study on Pennsylvania dairies, Dell et al. (2008) examined the impact of no-till and rye cover crops on soil C and N pools. They reported increased C and N pools in the no-till fields, with an estimated sequestration rate of 0.5 Mg ha^{-1} $yr.^{-1}$. Similarly, in a synthesis of Eagle et al. (2011) reported that conversion from conventional to no-till would result in 1.08 t CO_2 -e. ha^{-1} $yr.^{-1}$. Furthermore, integration of livestock into cropping systems may result in similar soil C retention and GHG loss (Savian et al., 2014; Figueiredo et al., 2017; Moraes et al., 2017). However, the time horizon for soil C sequestration rates to occur after changes to management is unsettled, and soil's may reach a saturation point (Hassink, 1997).

Anaerobic manure digesters are a closed system that take animal manure and utilize microbial fermentation to break down organic material into biogas which can be used as a source of natural gas, which can be used to generate electricity (Montes et al., 2013). The digestate, e.g., livestock bedding, fertilizer, and soil amendments, can be used on farm or sold as co-products. The biogas is captured, and the energy produced from that gas can be used for heat, electricity, and vehicle fuel. In the beef industry, emissions from manure management are relatively small in comparison with enteric CH_4, however manure management accounts approximately 45% of direct emissions from dairy cattle (EPA, 2024). This has largely been driven by a shifting in dairy operations to liquid manure handling systems (Lee et al., 2013). Manure management protocols to quantify baseline and project emissions with the equation: Offsets = Baseline emissions – (project emissions + leakage emissions) (Lee et al., 2013). Leakage, i.e., methane lost through digestor walls and piping, can be a significant source of emissions, which requires producers to invest in ongoing maintenance costs (Montes et al., 2013).

The amount of offsets produced per project depends greatly on the protocols used. For on farm applications, there are several different types of commercial digesters (Roos et al., 2004; Sharvelle and Loetscher, 2011; EPA, 2021). The simplest and most common is covered lagoons, which utilize manure with less than 3% solid content, and have longer hydraulic retention times relative to other systems (Montes et al., 2013; EPA, 2021). However, this type of digester is not practical in colder climates as too little CH_4 is generated (Sharvelle and Loetscher, 2011). Another common digester is plug-flow digesters (EPA, 2021). These digesters utilize manure with a solids content around 12%–15%, are typically heated to 30°C–38°C mesophilic temperature, and yield higher amounts of CH_4 (EPA, 2021; Steward et al., 2021; Montes et al., 2013). Lastly, complete mix digesters are another common digester type that utilizes a medium level of solids content (Steward et al., 2021). This digester is similarly heated to 30°C–38°C and mixes the manure content to spread the nutrients evenly throughout the reactor (Sharvelle and Loetscher, 2011). The type of manure and co-product inputs as well as type of digester being utilized, and number of animals results in a wide range of measured emission reductions (EPA, 2021). Of the digesters in the EPA AgStar database, the estimated range of annual emission reductions is 4 to 390,000 Mt. CO_2 -e. $yr.^{-1}$ (EPA, 2021). However, DeVuyst et al. (2011), in an economic analysis of a feedlot installing a manure digester found that the infrastructure investment required to install a manure digester was unfeasible for beef cattle. Cowley and Brorsen (2018) found that for dairy producers, economic feasibility was achieved when marketing co-products but not for CH_4 production alone. In the United States, the largest driver in digester installation has been the California Low Carbon Fuel Standard which has provided some regional incentives but is limited nationally (AcMoody and Sousa, 2020). This economic feasibility may be a roadblock in beef systems but potentially as pressure to act on climate change increases it may become more economically feasible for more operations. While anaerobic manure digesters are a viable option for insetting within animal agriculture systems to produce offsets, the barriers for adoption are currently limiting widespread adoption unless producers are being incentivized to install them.

Renewable energy can be implemented in a variety of systems and ways (Rosa and Gabrielli, 2023), and provides an avenue for producers to also receive monetary payments for their use outside of only offsetting climate impacts. Options include agrivoltaics systems, where crops are grown and/or animals are grazed below solar panels, other voltaic systems to produce solar energy, or wind turbines to produce wind energy (Chel and Kaushik, 2011). Currently, many of these technologies applications in agricultural systems are not widely adopted but decarbonization has the potential to reduce agricultural emissions globally by 720 MMT of CO_2-e per year (Rosa and Gabrielli, 2023). It should be mentioned, however, that a carbon myopic focus and drive toward renewable energy development in agriculture should not come at the cost of functional landscapes.

5.2 Pathways to climate neutral

It is possible that animal agriculture could achieve climate neutrality with both increased utilization of mitigation strategies and increased use of offsets. The ability to reach climate neutrality greatly depends on the individual system, and the accuracy of implementation of mitigation management strategies. If one defines net zero as net zero CO_2 emissions, then animal agriculture is likely capable of reaching net zero. Reducing only CO_2 emissions is an achievable goal for animal agriculture because the industry primarily produces CH_4 and N_2O. Reaching net zero CO_2 would involve switching from fossil fuels to renewables and offsetting any additional CO_2 emissions with carbon sequestration. However, for net zero emissions, or climate neutrality, this would include enteric CH_4, and manure N_2O and CH_4 would require substantial reductions and offsets (Ungerfeld et al., 2022). The potential to achieve this goal for cattle production will also greatly depend on the choice of metric (e.g., GWP100 or GWP*). Metric selection will be heavily scrutinized if GWP* is the metric of choice, regardless of the accuracy of that metric (Meinshausen and Nicholls, 2022). If this is the chosen metric, cumulative CO_2-we should be utilized as the year-to-year volatility of a rate-based metric leaves it highly susceptible to manipulations making a single year not reflective of the long-term direction of emissions. Further, the ability to achieve climate neutrality also depends on the scale of production. Climate neutrality for each individual small producer may not be possible, but climate neutrality for larger systems, companies in the supply chain, or countries may be possible. Some regions may also have a greater ability to reduce emissions or become net zero than other regions. For instance, as detailed in the discussion above, areas with high rainfall and productive grasslands may have a greater ability to offset emissions of the final product through C sequestration compared to more arid regions.

As both the U.S. beef and dairy industries have stated goals to achieve climate neutrality (or net zero emissions) emissions by 2040 and 2050, respectively, it is worth exploring how these sectors can realistically reach these targets. While these industries are both dependent on ruminant animals, they have vastly different emission profiles and therefore need different tools and strategies to achieve their goals. For example, in 2022 the U.S. dairy sector emitted 48.94 MMT CO_2-e emissions from enteric CH_4 and 44.34 MMT CO_2-e emissions from manure CH_4, compared to 136.94 and 4.31 MMT CO_2-e emissions from beef cattle enteric and manure CH_4, respectively (EPA, 2024). These statistics are only reflective of direct emissions, yet they indicate that reductions in enteric CH_4 will be critical for the beef industry, whereas the dairy industry needs to focus on both enteric and manure emission sources simultaneously. As discussed previously, the rates change in dairy manure emissions indicates this source may be the lead climate warming contributor from their supply chain (Beck et al., 2023a). Additionally, the choice of metric will be highly influential and likely dictate whether these goals are met.

To examine pathways to net zero emissions for both U.S. beef and dairy production, we utilized U.S. EPA (2024) estimates for direct CH_4 and N_2O emissions from 1990 to 2022. It should be reinforced, the emission data is from direct emissions from enteric and manure sources alone and does not encompass all emission sources from beef and dairy production. All data was reanalyzed using GWP* like the approach of Beck et al. (2023a) and is reported as both GWP100 and GWP*. While these pathway scenarios only include direct emissions, these emission sources are the largest for each sector and the EPA database provides the most robust time series data from which to project emissions into future years (Rotz et al., 2019; Rotz et al., 2021). Information on the database and EPA methods for emissions estimates is reported in Beck et al. (2023b). For GWP* and GWP100 estimates, 2010 was utilized as the baseline year for each scenario to calculate cumulative warming estimates to provide an equal representation of emissions impacts using both climate metrics. For future emissions from 2023 through 2050, annual estimates were calculated for each year based on the regression lines associated with each emission source (enteric CH_4, manure CH_4, and manure N_2O) for both beef and dairy cattle. For these sources, all emissions, with the exception of enteric CH_4 from beef cattle, are projected to increase in future years at rates of: Dairy enteric CH_4 = 9.3 kt CH_4/yr.; Dairy manure CH_4 = 23.9 kt CH_4/yr.; Dairy manure N_2O = 0.0898 kt N_2O/yr.; Beef enteric CH_4 = −6.4 kt CH_4/yr.; Beef manure CH_4 = 3.7 kt CH_4/yr.; Beef manure N_2O = 0.058 kt N_2O/yr. Year 2050 was chosen as the end date for projections as this would encompass both the U.S. Beef industry and U.S. Dairy industry climate commitments as outlined in Table 2.

We examined 5 different future scenarios (Table 5) for each beef (Figure 3) and dairy (Figure 4): (1) Business as usual (BAU) with only projected future emissions and no mitigation, (2) Scenario with an instantaneous 23% reduction in enteric CH_4 only (Sc1), (3) Sc1 stacked with an additional instantaneous 10% reduction in enteric CH_4 (Sc2), (4) Sc2 stacked with an instantaneous 30% reduction in manure emissions from both CH_4 and N_2O (Sc3), and (5) Plausible mitigation reductions over time (Sc4; described further below). Sc4 is unique for each beef and dairy production, based on literature estimates for realistic emission mitigation from all sources. For the beef industry (Sc4-Beef), the scenario was modeled to include a 23% reduction in enteric emissions by 2040 relative to 2022 (Place et al., 2022; Thompson and Rowntree, 2020) that was applied annually at a rate of 1.27%. No manure emission mitigation was included in this scenario due to their relatively small contributions (EPA, 2024; Rotz et al., 2019). For the dairy scenario (Sc4-Dairy), the same 23% reduction in enteric CH_4 was included by 2040. For manure emissions, CH_4 was modeled to achieve an 85% reduction by 2033 under the assumption all potential dairies who could adopt this technology do so (EPA, 2018). Under this same assumption, N_2O emissions were modeled to be reduced 70% over this same period (Montes et al., 2013). After the first 10 years, manure emissions were projected to continue the annual change as described above. These Sc4 scenarios were developed to be "realistic" to reflect slow adoption rates of new technologies and were like pathway estimates done previously (Place et al., 2022), with the difference being the forecasted emission rates in the future. Further, all scenarios examined here provide insights into the choice of metric selected when an organization goal sets and how this choice influences their ability to meet such goals. The methods used to achieve these reductions will likely come from multiple avenues such as changes in feed/forage quality, changes in genetics, and use of new technologies, to name a few. There will likely not be a single "silver bullet" approach that fits the all the production environments and methods that exist in the U.S. for both the beef and dairy sector.

For beef cattle (Figure 3), under the BAU scenario both cumulative CO_2-e. and CO_2-we emissions increase consistently, although the implied warming impact is considerably lower when using CO_2-we compared to CO_2-e. This is reflected in the beef industry goal setting year of 2040 with a CO_2-e. of 4,551.18 MMT/CO_2-e. vs. 1,146.18 MMT/CO_2-we. For CO_2-we, beginning in 2042 the annual change in climate warming becomes consistent year over year with an annual increase of approximately 40 MMT CO_2-we. For Sc1 through Sc3, all results were similar with respect to CO_2-e. and CO_2-we; however, there were marked differences between the two metrics. As one would expect when using the traditional GWP100 metric when calculating CO_2-e. the cumulative impact of beef emissions continued to rise through the end of the scenarios in 2050 for each of Sc1, Sc2, and Sc3. However, when using the GWP* approach, the cumulative CO_2-we reached negative values in 2026, 2025, and 2025 for Sc1, Sc2, and Sc3, respectively. This indicates that a sudden switch in management (indicative of policy and technology converging to cause producers to suddenly change management across the industry) can result in the beef industry quickly providing a net positive effect. However, this is not a permanent solution and will change as the industry would have reached a new baseline for emissions which can be found in year 2042 for all three scenarios. After this year, warming impacts begin to rise through 2050 and if this were to be projected out further, additional interventions would eventually be required as the industry would again become a net emitter at a future point.

The sudden changes in management described by Sc1–Sc3 are not likely to occur, and therefore Sc4-Beef was utilized to explore a more realistic, slow adoption of new technologies. For Sc4-Beef, CO_2-e. followed similar trends as Sc1 through Sc3, increasing consistently through 2050 and cumulatively was the second highest CO_2-e. scenario behind BAU. For CO_2-we, the cumulative warming increased slightly after emission reductions began, peaking in 2026, then began to decline and ultimately achieved a negative CO_2-we value in the year 2039. This demonstrates that by modest yearly reductions in enteric

TABLE 5 Emission mitigation scenarios for U.S. beef and dairy.

	Industry	
Scenarios	Beef	Dairy
Business as Usual (BAU)	Future emissions rate change: enteric CH_4 = −6.4 kt CH4/yr., manure CH_4 = 3.7 kt CH_4/yr. manure N_2O = 0.058 kt N_2O/yr	Future emissions rate change: enteric CH_4 = 9.3 kt CH_4/yr., manure CH_4 = 23.9 kt CH_4/yr., manure N_2O = 0.0898 kt N_2O/yr
Scenario 1 (Sc1)	Instant 23% reduction in enteric CH_4	Instant 23% reduction in enteric CH_4
Scenario 2 (Sc2)	Sc1 + additional 10% reduction in enteric CH_4	Sc1 + additional 10% reduction in enteric CH_4
Scenario 3 (Sc3)	Sc2 + instant 30% reduction in manure emissions	Sc2 + instant 30% reduction in manure emissions
Scenario 4 (Sc4)	23% reduction in enteric CH_4 by 2040	23% reduction in enteric CH_4 by 2040 + 85% reduction in manure CH_4 by 2033 + 70% reduction in manure N_2O by 2033

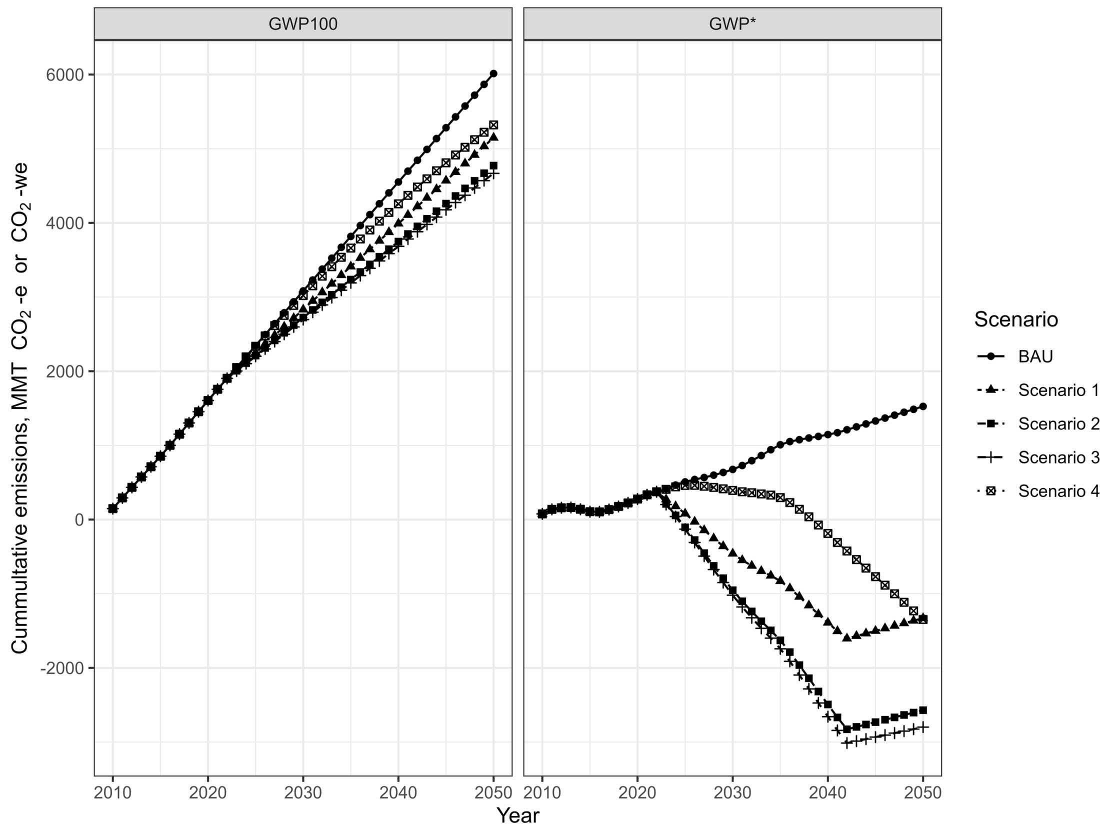

FIGURE 3
U.S. beef modeled climate scenarios. Business as usual (BAU) = only projected future emissions and no mitigation; Sc1 = a 23% reduction in enteric CH_4 only; Sc2 = Sc1 stacked with an additional 10% reduction in enteric CH_4; Sc3 = Sc2 stacked with a 30% reduction in manure emissions from both CH_4 and N_2O; Sc4-Beef = Plausible mitigation reductions over time, modeled to include a 23% reduction in enteric emissions by 2040 relative to 2022 (Place et al., 2022; Thompson and Rowntree, 2020) that was applied annually at a rate of 1.27%. No manure emission mitigation was included.

CH_4, the U.S. beef industry can realistically achieve neutral CO_2-we by 2040 in accordance with industry goals, however, this is not true when using CO_2-e emissions. Therefore, choice of accounting metric will be important when analyzing goal success and whether emission reductions or emission offsetting/insetting will be required.

Similar for the beef industry, for dairy (Figure 4), under the BAU scenario, both CO_2-e. and CO_2-we emissions increased consistently through the end of the modeled scenarios. However, one key difference relative to beef cattle, is that cumulative CO_2-we were actually greater throughout this scenario compared with CO_2-e. This was due, in part, to the large increase in emission changes year-over-year, particularly the increase of 23.9 kt of manure CH_4 each year, and no downward trends from any emission sources. Interestingly, while cumulative CO_2-e. was still lower than that of beef cattle in 2050 (3,993.75 vs. 6,013.49 MMT, for dairy and beef, respectively) the CO_2-we was roughly 180% higher for dairy cattle that same year (4,281.21 vs. 1,525.76, for dairy and beef, respectively). For Sc1 through Sc3, the behavior of CO_2-e. and CO_2-we metrics were similar within the metric of choice, but had divergent directional trends and rates of change. For CO_2-e., the cumulative impact of emissions continued to rise throughout the modeled scenarios as one would expect, with the more aggressive Sc3 having the lowest cumulative CO_2-e. For Sc1 and Sc2, cumulative CO_2-we never reduced, but did slow down slightly through the year 2042. After this year, annual changes to cumulative CO_2-we began to increase and continued to do so through 2050. However, for Sc3, cumulative CO_2-we did decrease year-over-year from 2023 through 2042, although negative cumulative CO_2-we were never achieved (676.65 MMT CO_2-we in 2042; Figure 4). After 2042, the new baseline had been achieved and cumulative CO_2-we began to rise again.

As described above, the Sc4-Dairy scenario was designed differently than what was used for beef to achieve more reductions from manure emission sources, which have been increasing in recent years. While CO_2-e. followed similar trends to other scenarios, the CO_2-we did result in the lowest cumulative warming impact of all scenarios, and continued to decrease, albeit at a diminishing rate, through the end of the modeled years. However, where this scenario in beef resulted in negative values by 2039, Sc4-Dairy did not achieve negative values until 2049 and reached a low in 2050 at −91.96 MMT CO_2-we. This change in time horizon for dairy represents the significance of both enteric and manure emission sources for this industry, relative to beef production, and the need to reduce both sources simultaneously to meet industry goals.

5.3 Roadblocks to climate neutrality

As outlined in the above section, Sc.4-Beef and Sc.4-Dairy were able to achieve the industry stated goals of climate neutrality by the

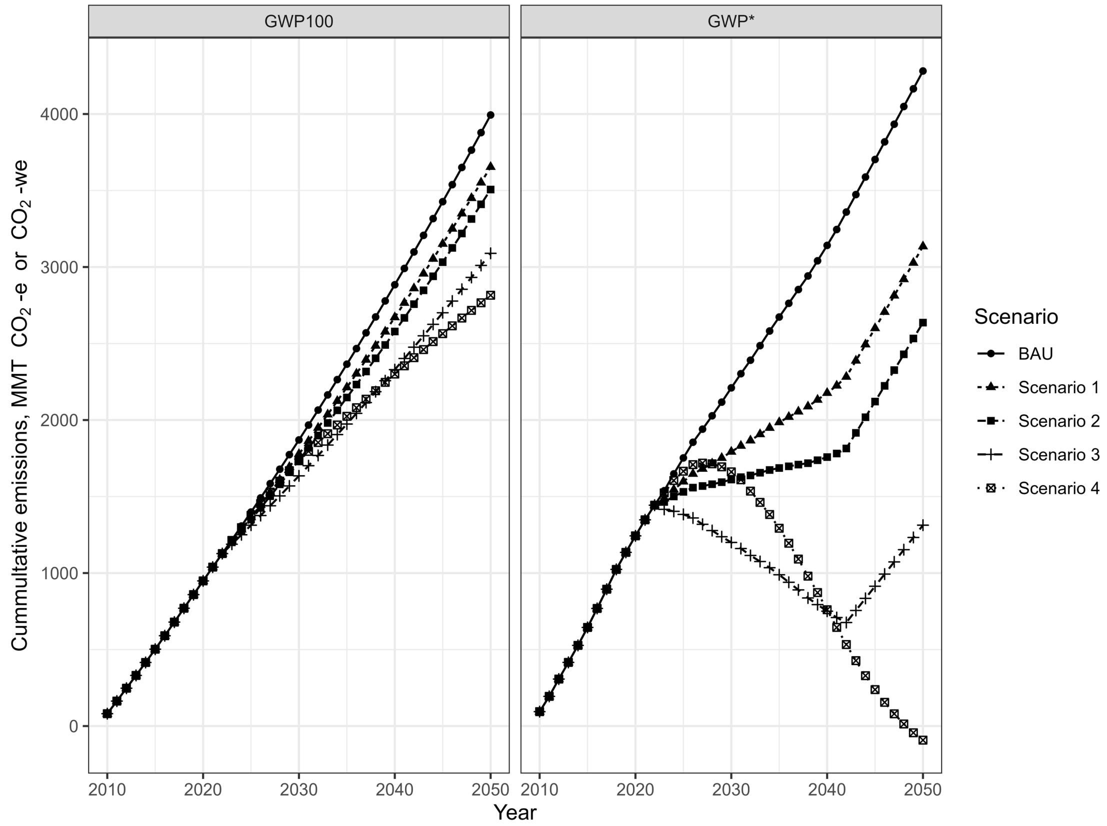

FIGURE 4
U.S. dairy modeled climate scenarios. Business as usual (BAU) = only projected future emissions and no mitigation; Sc1 = a 23% reduction in enteric CH4 only; Sc2 = Sc1 stacked with an additional 10% reduction in enteric CH_4; Sc3 = Sc2 stacked with a 30% reduction in manure emissions from both CH_4 and N_2O; Sc4-Dairy = Plausible mitigation reductions over time, 23% reduction in enteric CH_4 by 2040. For manure emissions, CH_4 was modeled to achieve an 85% reduction by 2033 under the assumption all potential dairies who could adopt this technology do so (EPA, 2018). Under this same assumption, N_2O emissions were modeled to be reduced 70% over this same period (Montes et al., 2013).

goal year from direct emission sources, 2040 and 2050 for beef and dairy, respectively. This section will discuss the roadblocks that are underlying for each respective industry and knowledge gaps that must be addressed for these goals to be achieved. As the U.S. beef and dairy industries are inherently different in their management and production design, roadblocks will be discussed for each separately.

Starting with beef cattle, a 23% reduction in enteric CH_4 emissions by the year 2040 applied at a constant annual change of 1.27% reduction per year was able to achieve climate neutrality from direct emissions. This relatively small reduction in emissions appears plausible at face value with efficacy of 3-NOP appearing purpose fit for such a reduction. However, as outlined in a LCA of U.S. beef production, Rotz et al. (2019) found that approximately 75% of methane emissions arose from the cow-calf sector and an additional approximately 12% come from stocker/backgrounding operations. These are predominantly grazing based production systems, where technologies such as 3-NOP have not been widely studied. This same logic applies to all similar mitigation options. Little is understood on how best to dose/supplement these technologies to maximize emission reduction in pasture, and therefore the magnitude of emission reductions is unclear for these sectors. Additionally, interest in soil carbon sequestration in grazing landscapes has increased considerably over recent years. As highlighted in the above section on offsets and insets, soil carbon sequestration potential is highly variable and not all landscapes hold the same potential for carbon storage, and changes to management can lead to small changes in soil carbon sequestration (Bai et al., 2019; Minasny et al., 2017). Furthermore, rangeland soils have been observed to have more heterogeneity than cropland soils which makes measuring and monitoring changes over time incredibly challenging (Stanley et al., 2023). For meaningful soil carbon sequestration rates to occur, more research needs to be conducted to improve soil carbon measurement protocols across different landscape types, and locally specific management scenarios to improve recommendations to producers. Lastly, while manure emissions were not required to be reduced from the beef specific climate neutrality scenario (Sc.4), manure gaseous losses such as ammonia still represent negative environmental externalities beyond GHG emissions including eutrophication of waterways, leaching into ground water, wet nitrogen deposition, and air pollution. These other externalities should not be in absentia in the larger conversation on climate neutrality. Progress needs to occur across all areas if environmental sustainability is to be truly achieved.

For dairy cattle production, the recent announcement on the approval of 3-NOP for dairy usage in the U.S. represents a feasible pathway to reduce emissions in the rates modeled here. Additionally, as this sector is largely fed in confinement in the U.S. less unknowns exist with its reduction potential. However, the adoption rates and potential for digester installation on dairy farms could hinder progress for this sector. In a recent survey of U.S. dairy producers, those who did not have digesters highlighted belief that the costs exceeded the benefits, and that they viewed their operations as being too small and there being no system designed for their scale (Cowley and Brorsen, 2018).

There has been success at the state level with the California Department of Agriculture funding dairy digester projects. However, the current rate of adoption for digesters is still limited by economics across the U.S., which is driven by renewable energy programs (Greene et al., 2024). The economic limitation represents a large roadblock to adoption. Further incentives programs will be needed to facilitate adoption across different regions and a range of production sizes. Digester technology improvements will be necessary to remove the gap in emission reduction potential that occurs across regions, as highlighted by Greene et al. (2024). A range of 58.1%–79.8% emission reduction potential was observed for large dairies across different regions. While this range was within that modeled here, improving digester usage in less efficient regions will aid the industry in achieving climate neutrality. Additionally, when digester installation is not practical, alternative manure management practices need to be incentivized to further reduce emissions where digesters are unavailable (McCabe et al., 2023).

6 Conclusion

Determining the ability of a system to be climate neutral is a complex and complicated process and will not be achieved by a "silver bullet" approach. Rather, the scientific community has, and will need to continue to, develop multiple producer friendly mitigation tools and approaches will need to be tailored based on region and producer context, which was outside of the scope of the modeled scenarios presented here. For example, producers in regions with higher rainfall with the ability to sequester soil C may not need as drastic of reductions in other emission sources as those in more arid environments where soil C is at a long-term equilibrium (Derner et al., 2019; Rowntree et al., 2020). Additionally, to truly determine if a system is climate neutral or not requires more accurate modeling of GHG emissions.

From the modeled scenarios presented here, climate neutrality is feasible for both the U.S. beef and dairy sectors but will not be without its challenges. For the beef sector, reduction in enteric CH_4 emissions at an annual rate 1.27% will result in climate neutrality by the industry stated goal of 2040. However, the lack of research on mitigation in grazing sectors will limit the near-term potential for reductions in the sector that producers the majority of enteric CH_4 emissions. For the dairy sector, the near equivalent enteric and manure CH_4 emissions will require simultaneous reductions from both sources to meet the industry stated goal of 2040. Further, with the rapid rate of increase in manure CH_4 emissions, concomitant rapid reductions from this source will aid reducing achieving the target when using GWP*.

The choice of metric will also play an important role in achieving climate neutrality. No scenario was able to achieve neutrality with emission reductions alone when using GWP100, making mitigation efforts of limited use even in the most aggressive mitigation scenarios. If this accounting method remains the primary metric, considerable offsets will be required to achieve neutrality for the beef and dairy industries. If GWP* is utilized to account for more accurate warming impacts, both industries will have a pathway for neutrality and to offset historic emissions from 2010 and potentially beyond. However, this choice could be met with criticism by opponents of this metric, who have highlighted the high degree of variability in annual GWP* values (Meinshausen and Nicholls, 2022). The scenarios presented in this paper have climate neutrality relative to a baseline year (when EPA data is able to be used with GWP*) with cumulative emissions equal to zero being considered as neutrality. This is likely more aggressive than industry commitments lend themselves, but demonstrate that realistic emission reduction targets for U.S. beef and dairy can offset past and ongoing warming impacts via mitigation strategies. Lastly, achieving climate neutral emissions does not equate to a sustainable production system, as it only encompasses GHG emissions, rather it is crucial to consider social and economic impacts of management changes (the other two pillars of sustainability) to achieve long term success. Making a change to reduce environmental impact that also decreases income or social wellbeing is not a sustainable system (Jablonski et al., 2020). Therefore, the progress to climate neutral must balance this target with social and economic outcomes.

Author contributions

LT: Conceptualization, Data curation, Investigation, Resources, Writing – original draft, Writing – review & editing. MB: Data curation, Investigation, Resources, Software, Visualization, Writing – review & editing. HL: Writing – review & editing. JR: Writing – review & editing. SP: Conceptualization, Investigation, Writing – review & editing. KS-L: Conceptualization, Investigation, Methodology, Supervision, Writing – original draft, Writing – review & editing.

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