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The Impact of Climate Change on Economic Losses and the Performance of Global Dairy Production for Food Supply

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ABSTRACT

Climate change represents a major challenge to global agricultural systems, with the dairy sector being particularly vulnerable to environmental fluctuations, which may negatively affect both the quantity and quality of milk. This study aims to analyze the impact of climate change on the efficiency and economic losses of dairy production systems and explore appropriate adaptation strategies to ensure the sector's contribution to meeting global food demand. This study utilizes a qualitative descriptive research technique, focusing on assessing the effects of climate change on the efficiency and economic losses of dairy production to secure the global food supply. The results revealed a clear relationship between climate stressors, economic losses, decreased productivity, and efficiency in the dairy sector, especially in regions with limited adaptive capacity. However, the adoption of climate-smart practices such as using heat-resistant breeds, improving feed management, and applying sustainable agricultural techniques resulted in positive effects on both environmental and economic sustainability. To safeguard global food security, there is an urgent need to adopt integrated adaptation strategies, including investment in research and technology, policy support for sustainable practices, and capacity building for farmers. Furthermore, international cooperation will be essential to enhance the resilience of dairy production systems in the face of climate change.

Keywords: Climate Change; Dairy Production; Economic Losses; Food Security; Milk Production

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1. Introduction

In recent years, the global climate has experienced profound transformations, characterized by increasingly erratic and volatile weather conditions expected to intensify in the near future. A key driver of the marked increase in average global temperatures is the elevated release of greenhouse gases (GHGs) caused by human activities. These emissions, including primarily nitrous oxide (N_2O), carbon dioxide (CO_2), and methane (CH_4), are directly linked to disruptions in precipitation patterns and the growing frequency and severity of extreme weather events such as floods and droughts. The ongoing accumulation of these gases in the atmosphere is fundamentally reshaping climate dynamics across the planet [1].

The Fifth Assessment Report by the Intergovernmental Panel on Climate Change (IPCC) highlights that climate change is expected to bring about major shifts in key environmental factors such as temperature, rainfall, humidity, atmospheric CO_2 concentration, and water resources—all of which are likely to negatively impact agricultural productivity [2]. Research indicates that total annual rainfall could decline by 15–30%, alongside a gradual expansion of arid desert regions into areas currently classified as temperate zones. These shifts, driven by increasing temperatures and diminishing precipitation, are anticipated to have serious repercussions, particularly for livestock farming and crop production, thereby posing a significant threat to global food security [3]. Additionally, projections suggest that average global surface temperatures could rise between 0.3 °C and 4.8 °C by the end of the century [4].

Livestock, particularly the dairy sector, plays a crucial role in ensuring global nutritional security by supplying essential food products. Beyond its nutritional value, livestock has historically served as a key asset for human livelihood and remains a primary source of income for many rural communities. This positions the livestock industry as a cornerstone of global agriculture, contributing significantly to national and international economies. However, livestock farming is heavily dependent on natural resources and is frequently associated with environmental concerns, such as land degradation and the excessive use of water. Furthermore, the sector is a notable contributor to greenhouse gas emissions, generated through multiple processes including enteric fermentation, land use alterations, fertilizer application, pasture and feed management, manure handling, and transportation. These emissions play a substantial role in accelerating climate change [1]. Notably, Boudebbouz et al., reported that livestock is responsible for over 83% of emissions originating from the agricultural sector [5].

Conversely, livestock production systems are becoming increasingly vulnerable to the intensifying patterns of extreme climate change, placing additional strain on the livelihoods of impoverished and marginalized farming communities [6]. The influence of climate change is not uniform; it differs widely based on geographic location, exposure duration, and the distribution of climatic events. Moreover, the effects vary considerably among livestock species, breeds, and even individual animals. In the dairy sector, climate fluctuations have a profound impact across the entire value chain, affecting animal physiology, well-being, health status, reproductive performance, and productivity levels. These challenges become especially severe during periods of extreme heat, such as heatwaves and prolonged warm spells. Elevated temperatures negatively affect milk yield and composition, reducing both the volume and nutritional quality of dairy products. Such declines can result in major economic losses for the dairy industry [7].

Consequently, the growing impact of climate change underscores the urgent necessity to implement both adaptation and mitigation strategies. These measures encompass improved management practices, tailored nutritional approaches, proactive health care, and targeted breeding programs, particularly focusing on genetic traits that enhance animals' resilience to heat stress, to safeguard the productivity of high-performing livestock [8]. Additionally, boosting efficiency and output across agricultural systems, especially in the livestock sector, is essential not only for promoting environmental sustainability but also for driving economic development, securing global food supplies, and protecting public health [9].

This study seeks to emphasize the critical importance of dairy production in ensuring global food security, while also examining the significant challenges that climate change presents to this sector. It further explores practical and strategic solutions aimed at building resilience and promoting sustainable productivity and economic losses within dairy systems. To guide this exploration, the research focuses on three central questions designed to provide comprehensive insights into the key issues at hand, as well as to evaluate the effectiveness of various strategies for mitigating the impacts of climate change on dairy production. The core research questions include:

Q1- What is the role of dairy production in global food security?
Q2-What is the impact of environmental factors on the resilience and productivity of dairy production?
Q3-How Does Climate Change Economically Impact Milk Production Efficiency and Sustainability?
Q4-What strategies can be implemented to overcome climate change and enhance the efficiency of global dairy production?

Identifying and understanding the key challenges and obstacles to sustainable dairy production is essential for ensuring long-term food security under changing climatic conditions. Rising temperatures, irregular rainfall, and the increasing frequency of extreme weather events pose significant risks to production efficiency, economic returns, and farm productivity, often leading to reduced outputs and deteriorating animal health. Although numerous previous studies have examined the effects of climate change on dairy productivity or focused on estimating economic losses at the farm level, research directly linking these localized economic impacts to their broader implications for global food security remains highly limited. This constitutes the research gap that the present study seeks to address by providing a comprehensive analysis of climate-related risks and their impact on the efficiency of dairy production, while also clarifying how the economic challenges driven by climate change affect the sector's capacity to meet global food demand. The study further evaluates a range of innovative approaches, including the adoption of diverse management techniques, breeding livestock with greater climate resilience, and implementing optimized feeding practices, thereby offering valuable contributions to the global discourse on food security. In conclusion, the study emphasizes the importance of adopting proactive adaptation strategies to strengthen dairy production systems, enabling them to withstand future environmental pressures, maintain sustainable and efficient output, and minimize economic losses.

2. Materials and Methods

This study adopts a qualitative descriptive research methodology to analyze the influence of climate variability on the sustainability, economic losses, and performance of dairy production for the global food supply. Descriptive research, as outlined by Neuman [10], is distinguished by its ability to "present a picture of the specific details of a situation, social setting, or relationship" and "begins with a well-defined issue or question and endeavors to describe it accurately." It also focuses on addressing "how" and "who" inquiries. Moreover, qualitative research designs, including phenomenology and grounded theory, can serve both descriptive and explanatory purposes [11]. In addition, Lambert and Lambert advocate for the use of the term "qualitative descriptive research" to prevent misclassification with other methodologies such as phenomenology, grounded theory, and ethnography [11]. Their concept of "naturalistic inquiry" emphasizes that qualitative descriptive research seeks to observe phenomena in their natural state as much as possible within the research context [11]. The present study is qualitative because it analyzes the influence of climate change on sustainability, economic losses, and performance of dairy production for global food supply, confirming its classification as qualitative descriptive research. Furthermore, the study's objectives necessitate an in-depth content analysis of both electronic and printed materials related to the events under investigation [12]. According to Bowen, content analysis involves three key phases: skimming, comprehensive reading, and interpretation [12]. By segmenting extensive text into smaller, more manageable units, content analysis facilitates the identification of core meanings [13]. It achieves this by detecting recurring themes and patterns within the text[14]. Moreover, following Bowen's[12] three-phase model, including skimming, comprehensive reading, and interpretation, this research applies a systematic approach to analyzing electronic and printed materials. A structured review protocol was developed to enhance methodological transparency and reduce narrative bias. Inclusion criteria were established based on the publication date within the last five years alongside foundational references to provide theoretical context, language (English), type of source (peer-reviewed articles and credible international reports), geographical scope includes representative models from both developed and developing countries (such as the USA, India, Pakistan, China, as well as African and European nations), and thematic relevance (climate change and dairy production). Sources were excluded if they were outdated, non-peer-reviewed, or unrelated to dairy or climate issues. Key databases such as Web of Science, Scopus, and Google Scholar were searched using compound keywords including "climate change and dairy production," "heat stress in cattle," "milk yield," "economic losses", and "livestock adaptation." The selected literature was coded and categorized thematically to identify patterns, trends, and key insights across regions. This systematic content analysis enabled the extraction of evidence-based interpretations, improving coherence between research questions and findings. The structured approach strengthens the study's methodological rigor and allows for the formulation of relevant policy recommendations and strategic adaptation insights across diverse global contexts.

3. Results and Discussion

3.1. Dairy Production Plays a Vital Role in Strengthening Global Food Security

Milk and other dairy foods are indispensable sources of nourishment and income for millions of people worldwide. In most dairy value chains, particularly in low and middle-income nations, consumption is dominated by fresh or minimally processed items such as raw, pasteurized, or fermented milk, rather than highly processed products like butter, cheese, skim-milk powder (SMP), whole-milk powder (WMP), whey powder, or, in limited cases, casein. By contrast, consumers in wealthier countries tend to favor a wider range of processed dairy foods. Looking ahead, population growth is expected to drive a substantial uptick in dairy demand, especially in India, Pakistan, and several African countries[15].

Cheese stands out as the leading processed dairy product in terms of milk solids consumption across Europe, currently the world's top cheese exporter, as well as in North America and New Zealand. Looking ahead to 2032, the United Kingdom, Japan, Russia, the European Union, and Saudi Arabia are forecasted to become the five largest importers of cheese globally. In Africa, cheese represents the most widely consumed processed dairy product. Meanwhile, butter holds the top spot for processed dairy consumption in Asia and is expected to experience the most significant growth in that region. New Zealand remains the dominant global supplier of butter, with its market share projected to reach approximately 40% by 2032[15]. Due to the high cost of trading liquid milk, driven by its bulky volume-to-value ratio, anticipated increases in global dairy demand will likely be met through milk powders, including whole milk powder (WMP) and skim milk powder (SMP). New Zealand is also projected to maintain its position as the primary exporter of WMP, commanding around 60% of the global market by 2032. China is expected to retain its role as the world's leading dairy importer, with WMP imports from New Zealand playing a central role in meeting its demand. In Africa, WMP continues to be the dominant form of processed dairy consumption. Over the next decade, SMP is predicted to see the most rapid growth, largely because of its versatility and ease of trade in food manufacturing. Among major exporters, the United States is anticipated to be the most dynamic, particularly in scaling up SMP exports[15].

Globally, milk production, comprised of approximately 81% cow milk, 15% buffalo milk, and 4% from goats, sheep, and camels, is expected to rise significantly over the next decade, reaching an estimated 1,039 million tonnes (Mt) by 2032. This growth rate is projected to outpace that of most other major agricultural commodities. More than half of the projected increase will come from India and Pakistan, which together are anticipated to contribute over 32% of global milk output by 2032 [15]. According to FAO's latest market outlook, global milk production is estimated to reach around 979 million tonnes by mid-2024, representing a 1.4% increase compared to 2023 [16]. Asia leads this growth, with a year-over-year increase of 2.3%, pushing regional production to approximately 431 million tonnes. Europe, by contrast, is forecast to see more modest growth of about 0.5%, bringing its output to roughly 234 million tonnes [17]. Key milk producers on the global stage include India, China, Pakistan, Turkey, Uzbekistan, and Kazakhstan. India holds the position as the largest milk producer and is projected to sustain robust growth, reaching approximately 232 million tons. This expansion is driven by an increase in dairy cow populations, particularly among small-scale farmers, alongside the rising influence of more efficient, large-scale dairy operations achieving higher milk yields. Nevertheless, in most parts of the world, improvements in milk yield per animal are expected to contribute more significantly to production growth than simply expanding herd sizes. Such productivity gains can be attributed to enhanced milk production management, advances in animal genetics, better health care, and optimized feeding practices. Looking ahead, about 30% of the total milk produced globally is anticipated to be processed into value-added dairy products such as butter, cheese, skim milk powder (SMP), whole milk powder (WMP), and whey powder, with this trend being particularly pronounced in high-income countries. However, macroeconomic factors, including currency volatility and slower economic growth in key milk-producing regions, may dampen consumer demand for dairy products, which in turn could restrain the growth of milk production [16].

Only a small portion of the world's milk production, approximately 7%, is traded on the international market, largely due to milk's high perishability and its water content exceeding 85%. Consequently, international trade primarily involves processed dairy products, such as powders and cheese, which are manufactured to facilitate longer storage and transportation. In contrast, fresh dairy items are minimally traded, mostly consisting of small quantities of fermented products exchanged between neighboring countries [15]. Despite this, global dairy product trade is expected to reach 85.3 million tons in 2024, marking a 0.8% increase from 2023, with significant growth observed in countries such as Mexico, the Philippines, Saudi Arabia, the United States, Algeria, and Japan [16]. Meanwhile, China is projected to maintain its position as the largest importer of dairy products, despite notable increases in its domestic milk production over the past decade [15]. Moreover, Australia, the United States, New Zealand, Argentina, and the United Kingdom are anticipated to supply a substantial share of the expected rise in dairy imports, driven by competitive pricing and ample export capacity [16]. The future trajectory of the dairy trade will be influenced by the adoption of sustainable production policies, consumer acceptance trends, and evolving trade agreements, all of which may reshape global market dynamics. As a result, the world dairy trade is projected to expand steadily, reaching 14.2 million tons by 2032. This growth will be largely supported by exports from the United States, the European Union, and New Zealand, which together are expected to account for roughly 65% of global cheese exports, 70% of whole milk powder (WMP) and butter exports, and 80% of skim milk powder (SMP) exports by that year. Argentina is also forecasted to remain a key exporter of WMP, representing about 5% of world exports in 2032 [15].

Global dairy market trends are largely shaped by the export values of processed dairy goods from leading producers in regions like Oceania and Europe. Among the primary indicators used to track these values are butter, which is the standard for milk fat pricing, and skim milk powder (SMP), which reflects the pricing of non-fat milk solids. Combined, milk fat and other solids represent roughly 13% of the total weight of milk, with water making up the remainder. As a result, international prices for whole milk powder (WMP) and cheese typically mirror the price trajectories of butter and SMP, based on their respective fat and non-fat content ratios [15]. As reported by the FAO Dairy Price Index, international dairy prices saw a downward trend until September 2023. This was largely attributed to weakened demand, particularly for WMP, from major importing nations like China, which is the largest dairy importer globally. This decline was influenced by a slowdown in the growth of food service sectors and increased domestic production. Nevertheless, from October 2023, dairy prices began to recover, with cheese being the notable exception [17]. During the period from January to May 2024, global dairy prices increased by 6.2%, with significant gains recorded for butter and cheese. This rise was supported by ongoing international demand, stronger retail and food service sales, and tighter inventories in key production areas, most notably the European Union. On the other hand, WMP registered modest price growth, whereas SMP prices dropped due to continued weak import demand across global markets [16].

Table 1 shows that the European Union dominates milk production at around 145,000 metric tons annually, while its consumption remains relatively low (23,500–23,800), highlighting a significant role for exports or domestic processing. India demonstrates steady growth in both production and consumption, with production increasing from 97,000 to 103,000 and consumption rising from 85,000 to 91,000, reflecting growing domestic demand. China also shows notable increases, with production rising from 39,300 to 43,300 and consumption from 16,250 to 17,100, indicating expanding industry capacity and increasing domestic demand. Russia maintains moderate production (33,000) with low consumption (6600–7100), while Brazil and New Zealand show modest production increases, with New Zealand's minimal consumption (535) emphasizing its strong export orientation. Argentina and Canada exhibit slight fluctuations in production and consumption, with Argentina experiencing a noticeable decline in 2024, followed by a small recovery in 2025. Overall, the table illustrates gradual global production growth accompanied by moderate increases in consumption, with clear patterns distinguishing domestic demand from export-oriented production in specific countries.

Table 1. Top countries in Cow's Milk Production and consumption as "1000 Metric Tons" from 2022 to 2025 [18].

Country	2022		2023		2024		December 2025	
	Production	Consumption	Production	Consumption	Production	Consumption	Production	Consumption
European Union	144,378	23,800	145,122	23,785	146,00	23,833	145,300	23,550
India	97,000	85,000	99,000	87,050	101,000	89,000	103,000	91,000
China	39,300	16,250	41,970	16,500	40,790	15,700	43,300	17,100
Russia	32,978	7100	33,800	7100	34,072	7075	32,600	6600
Brazil	23,660	10,564	24,700	11,000	25,000	11,000	25,400	11,200
New Zealand	21,051	535	21,247	535	21,640	535	21,800	535
United Kingdom	15,447	6281	15,500	6200	15,685	6170	15,300	6150
Mexico	13,110	4166	13,333	4210	13,555	4260	13,650	4300
Argentina	11,904	1800	11,665	1715	10,910	1575	11,200	1400
Canada	10,178	2721	10,265	2705	10,340	2775	10,455	2810

On the other hand, milk and dairy products serve as a vital source of nutrition and income globally, with the sector undergoing continuous changes driven by population growth and increasing food demand, particularly in emerging markets. Consumption is largely dominated by fresh or minimally processed products, whereas higher-income markets tend to favor a broader range of processed dairy items such as cheese, butter, and milk powders, which also support international trade due to the high perishability of fresh milk. Global milk production is expected to increase significantly in the coming years, driven by productivity improvements per animal through advances in herd management, nutrition, health, and genetics, alongside the expansion of larger, more efficient production facilities. Additionally, processing a portion of milk into value-added dairy products plays a critical role in enhancing food security, meeting global demand, and supporting international trade. These trends reflect the dual challenges faced by the dairy sector: meeting growing domestic demand while maintaining competitiveness in global markets, necessitating the adoption of sustainable and resilient production policies to ensure stable, efficient, and economically viable output.

3.2. Environmental Factors Significantly Influence the Resilience and Productivity of Dairy Production

Changing climatic conditions represent one of the most significant challenges confronting dairy farmers across many parts of the world, and this issue is likely to become even more critical for the future of dairy farming. Climate change directly impacts dairy cattle by raising core body and skin temperatures, which in turn suppresses growth, milk and wool production, feed consumption, and reproductive performance, ultimately causing economic losses for dairy operations [19]. In response to thermal stress, dairy animals undergo a range of physiological, behavioral, and biochemical adaptations aimed at minimizing heat production and maximizing heat dissipation to maintain stable body temperatures. Common responses to heat stress include increased respiration rates, sweating, elevated water intake, reduced consumption and metabolism of dry matter and protein, vasodilation that increases blood flow to the skin, and changes in the efficiency of feed utilization and water metabolism. These physiological adjustments often lead to declines in milk yield and milk fat content. Furthermore, extreme heat and humidity create favorable conditions for increased contamination and pathogen growth [20]. Reduced feed intake under heat stress frequently results in negative energy balance (NEBAL), weight loss, and elevated levels of nonesterified fatty acids (NEFA) in the bloodstream [1].

On dairy cattle farms, the Temperature-Humidity Index (THI) is widely used to quantify heat stress by combining measurements of ambient temperature and relative humidity, serving as a reliable indicator of thermal comfort or discomfort [21]. As shown in **Figure 1**, heat stress in dairy cows typically begins when the THI surpasses 72. This stress can be categorized into four distinct levels: Mild heat stress occurs when THI ranges between 72 and 79. Within this range, cows adapt by seeking shade, increasing their respiration rate, and dilating blood vessels, although the impact on milk production is generally minimal [22]. Moderate heat stress is observed at THI values between 80 and 89, where cows exhibit increased salivation, elevated respiration rate, greater water intake, higher body temperature, and reduced feed consumption, all contributing to declines in milk yield and reproductive performance. Severe heat stress arises when THI reaches 90 to 98, causing pronounced increases in body temperature, rapid breathing, and excessive salivation, which can lead to health complications and significant drops in milk production and fertility. Finally, when THI exceeds 98, cows face dangerous levels of heat stress that may result in fatal outcomes if conditions persist [22].

However, the specific THI threshold at which cattle begin to experience heat stress can vary significantly [23]. This variation in the critical THI affecting milk production is often influenced by a range of environmental factors, including regional climate conditions, availability and effectiveness of cooling systems, and the degree of genetic advancement within the herd. These factors collectively shape how THI correlates with milk yield [22]. Furthermore, the effects of climate change on dairy production systems can be broadly categorized as follows:

3.2.1. Impacts of Climate Change on Performance, Milk Quality, and Reproduction

Milk production exhibits seasonal variation due to periodic environmental changes throughout the year, which directly impact milk yield by reducing dry matter intake and indirectly through changes in feed quality and availability [23]. When ambient temperatures rise above an individual animal's thermal comfort zone, body temperature increases, leading to decreased feed consumption [8]. This negative relationship between heat and feed intake is more pronounced in high-producing dairy cows, making them particularly susceptible to heat stress [24]. Milk production tends to decline when the Temperature-Humidity Index (THI) surpasses 80, with reductions of up to 50% attributed primarily to lower feed intake and increased resting time as metabolic adaptations to heat stress. However, other studies suggest that reduced feed intake explains only about 35% of the decline in milk yield caused by heat stress [1].

Heat stress adversely affects milk production by reducing the growth of mammary epithelial cells and disrupting energy metabolism, which limits the mammary gland's ability to efficiently use nutrients for milk synthesis due to disturbances in the hypothalamic-pituitary-endocrine axis [25]. Moreover, heat stress during the dry period, a critical phase for mammary gland rest and preparation for the next lactation, causes metabolic changes that reduce subsequent milk yield by about 5 to 7.5 kg per day [1]. In addition, excessive heat exposure during lactation shortens the length of lactation cycles, further decreasing overall milk production [22]. Research indicates that during periods of extreme summer heat, when the THI exceeds 80, the lactation period can be shortened by 3 to 7 days [26]. Elevated heat stress is also associated with increased cortisol levels in cows, which may further suppress milk production [27]. On the other hand, following the cessation of heat stress, milk yield can begin to recover; however, it often does not return to pre-stress levels [28]. The recovery period typically ranges from 2 to 5 days and is influenced by several factors, including individual animal responses, the severity and duration of the heat stress, as well as the maximum and minimum ambient temperatures during the recovery phase [19].

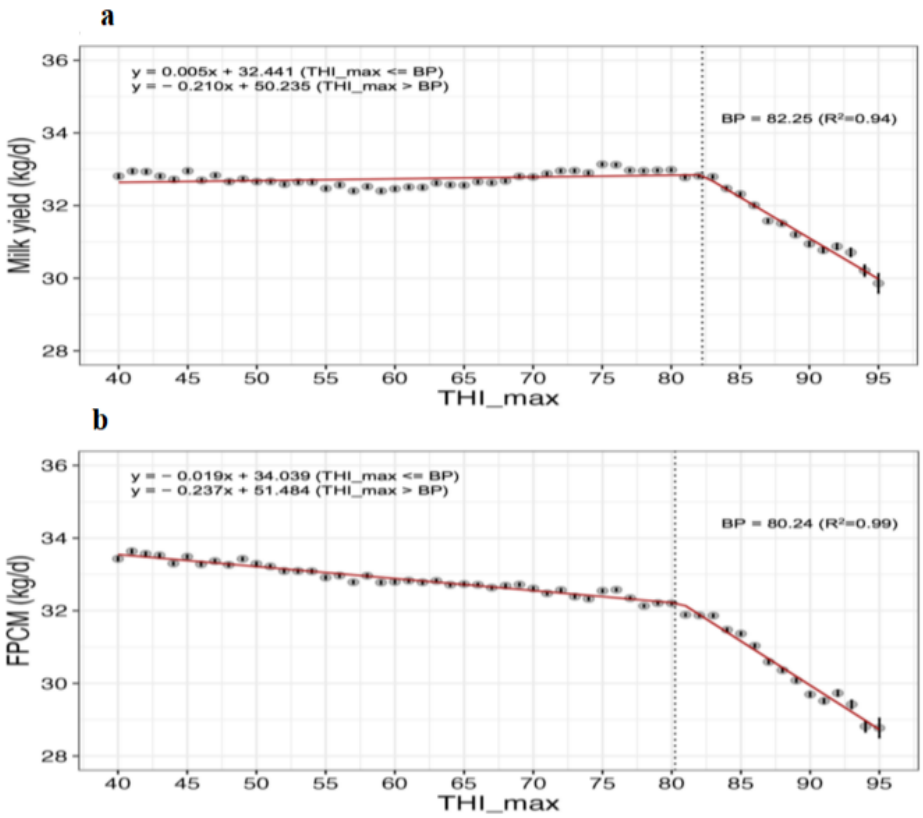

Figure 1. Least-square mean (Solid circles) and standard error (bars) indicate the association between heat stress (measured by THI_max, maximum Temperature-Humidity Index) and (**a**) milk yield and (**b**) fat and protein corrected milk (FPCM) in Holstein cows ($p < 0.05$). THI_max; BP, break points [22].

In addition to affecting milk yield, climatic changes, particularly heat stress, also influence milk quality, including both organic and inorganic components. Notably, milk composition tends to be more sensitive to heat stress than milk yield itself[1]. While some studies have reported no significant impact of heat stress on milk lactose content [7], other components are markedly affected. Heat stress has been associated with reductions in milk fat, changes in triacylglycerol profiles, altered phospholipid composition, and decreased levels of solids-not-fat. Moreover, both milk protein and casein concentrations tend to decline under heat stress conditions, which negatively influences milk coagulation properties and reduces cheese production efficiency, especially when raw milk is used [29]. The decrease in casein has been particularly linked to reductions in the proportions of α-casein and β-casein [30]. These compositional changes may, in part, be attributed to a dilution effect resulting from decreased dry matter intake and increased water consumption during periods of heat stress [23]. Additionally, somatic cell counts in milk have been reported to rise during the summer months, indicating a potential compromise in udder health and milk quality [31].

Both short- and long-term exposure to heat stress can lead to significant disruptions in the reproductive physiology and performance of dairy cattle, with fertility being particularly affected. Among the observed impacts are prolonged calving intervals due to an increased number of days open, reduced conception rates, and impairments in follicular development, including the quality of oocytes and embryos [32]. Heat-induced oxidative stress may further contribute to reproductive failure by increasing the incidence of polyspermy, thereby compromising the developmental competence of the zygote [33]. In pregnant cows, heat stress can directly affect the uterine environment, leading to negative consequences on embryo implantation and early fetal development. Additionally, male fertility is also vulnerable; heat stress can induce testicular hyperthermia in bulls, adversely affecting sperm quality and DNA integrity. Semen from heat-stressed bulls is often characterized by reduced motility and a higher proportion of morphologically abnormal spermatozoa [34].

In this context, heat stress poses a critical challenge to dairy production, affecting both milk quantity and quality as well as the reproductive performance of cattle. Elevated temperatures reduce feed intake and disrupt metabolic processes, resulting in significant declines in milk yield, alterations in milk composition—including reductions in fat, protein, and casein—and decreased cheese-making efficiency. These physiological impacts are further compounded by shortened lactation cycles, increased somatic cell counts, and incomplete recovery of milk yield even after heat stress subsides. Moreover, heat stress impairs fertility in both cows and bulls by affecting oocyte and embryo quality, extending calving intervals, and reducing sperm motility and integrity. Collectively, these effects underscore the urgent need for proactive heat mitigation strategies, integrated herd management, and nutritional and genetic interventions to sustain efficient, high-quality, and resilient dairy production under increasingly variable climatic conditions.

3.2.2. Impacts of Climate Change on Dairy Health, Behavior, and Welfare

As dairy production levels increase, so does the sensitivity and vulnerability of animals to environmental stressors, thereby intensifying the impacts on their health, behavior, and overall welfare [35]. The severity of these effects is influenced by several factors, including the animal's genetic makeup, duration and intensity of heat exposure, and reproductive status. Notably, exposure to heat stress during the later stages of gestation can compromise the uterine defense mechanisms, increasing susceptibility to uterine disorders such as metritis. This can negatively affect fertilization rates, impair early embryonic development, and heighten the risk of pregnancy loss [36]. Moreover, even short-term heat stress during the final phase of gestation may significantly affect the health, growth, and future performance of the offspring [37].

Animal health can be impacted by climatic conditions through both direct and indirect pathways. Direct effects include temperature-related illnesses, which are often associated with alterations in immune cell function and disruptions to the endocrine system in lactating cows [38]. Indirect effects primarily involve changes in feeding behavior, such as reduced feed intake in high-yielding dairy cattle, which increases the risk of metabolic disorders like subclinical or clinical ketosis [39]. Furthermore, climate change also affects the distribution and population dynamics of disease vectors and the pathogens they transmit, thereby potentially increasing the prevalence and spread of vector-borne diseases [8].

Dairy cows face significant challenges in coping with elevated temperatures and extreme heat waves, which heighten their susceptibility to various physical and physiological disorders. Prolonged exposure to high temperatures can negatively affect metabolic rate, endocrine balance, oxidative status, and the metabolism of glucose, proteins, and lipids. Additionally, liver function is often compromised, as indicated by reduced levels of cholesterol and albumin in affected livestock. Other physiological parameters, including non-esterified fatty acids (NEFA), salivation, and salivary bicarbonate concentrations, are also adversely impacted. These disruptions contribute to greater energy deficits, which can impair cow longevity, overall fitness, and productive performance [40].

Climate change, both present and projected, is also expected to influence the distribution and severity of pasture pests, weeds, and diseases. Rising global temperatures are shifting the geographical range of various insect species further north, enabling the spread of livestock diseases previously absent in these regions. Many of these diseases are vector-borne, transmitted by insects that require specific temperature conditions for growth and reproduction. Furthermore, the prevalence of parasitic organisms such as nematodes and liver flukes is anticipated to increase in warmer climates, presenting additional health challenges for dairy herds [40].

Climate change significantly influences the incidence and distribution of livestock diseases through various interrelated factors, including geographic shifts, land-use changes, animal susceptibility, and disease-specific characteristics. Rising global temperatures exert both direct and indirect effects on animal health, contributing to increased risks of morbidity and mortality, alterations in microbial ecosystems, wider dispersion of vector-borne diseases, and higher prevalence of food-borne illnesses [40]. Elevated temperatures, in particular, have been linked to the accelerated growth of parasites and the emergence of novel pathogens capable of causing substantial harm to livestock populations. Additionally, warmer climates enhance the probability of disease transmission among animal hosts, thereby intensifying biosecurity concerns [40].

Moreover, climate change–induced water scarcity and rising sea levels have led to the increased intrusion of saltwater into freshwater reserves. This intrusion results in the salinization of water bodies and the accumulation of heavy metals, chemical residues, and biological contaminants. Such pollutants not only degrade the quality of water available to livestock but also have detrimental effects on animal health, impairing digestive processes, reproductive performance, and metabolic functions. The bioaccumulation of heavy metals and toxic compounds further compromises multiple physiological systems and jeopardizes the hygienic quality of livestock products intended for human consumption [40].

Microbiological contamination of milk, particularly by pathogens such as Salmonella spp. and Staphylococcus aureus, is often associated with inadequate hygiene practices prevalent in traditional extensive livestock production systems. In such settings, animal manure and urea are common sources of contamination, especially when proper sanitation and milking hygiene are lacking [20]. Furthermore, animal manure is a significant contributor to greenhouse gas (GHG) emissions, accounting for approximately 25% of total emissions from the livestock sector. These emissions primarily consist of CH_4 and N_2O, both potent GHGs that contribute to global warming. A substantial portion of manure is produced in open fields or in housing systems that use straw or litter, where conditions often promote gas release. Moreover, Methane, in particular, is poorly soluble in water, which leads to its rapid release into the atmosphere from livestock housing facilities. This gas accumulation can degrade indoor air quality and facilitate microbial proliferation. As ambient environmental temperatures increase—an effect exacerbated by climate change, the rate of microbial growth and contamination risks also rise, further compromising milk safety and quality [41].

On the other hand, seasonal variation has a significant influence on the incidence rate of clinical mastitis in dairy cattle [1]. In Egypt, studies have demonstrated that milk from cattle exposed to elevated Temperature-Humidity Index (THI) values rose from 72 to 78, which exhibited increased levels of total somatic cell count, fecal coliforms, and Escherichia coli [42]. The quality and safety of milk are closely linked to the health status of the animal. Pathogens such as Staphylococcus aureus and E. coli have been frequently isolated from milk produced by cows exposed to THI values exceeding 72, indicating a direct correlation between heat stress and milk contamination [43]. According to Montcho et al., high concentrations of S. aureus in raw milk may be attributed to the occurrence of mastitis in heat-stressed animals [20].

The risk of microbial contamination increases rapidly under favorable conditions such as high ambient temperatures and elevated humidity, which promote bacterial growth and proliferation [44]. In addition to its impact on milk hygiene, heat stress significantly alters bovine behavior. Affected animals exhibit reduced overall activity levels [45], increased water intake, and a shift in feeding patterns toward cooler periods of the day [46]. Heat-stressed cows also demonstrate changes in standing and lying behaviors, which can suppress overt estrus signs, such as mounting, thereby negatively affecting reproductive efficiency [47].

Climate change poses significant risks to the health, behavior, and overall welfare of dairy cattle, with elevated temperatures and extreme weather events increasing animals' exposure to environmental stressors. Heat stress negatively affects physiological processes and metabolism, impairs immune function, and elevates the risk of reproductive disorders, particularly during late gestation. These impacts extend to offspring performance, influencing growth, health, and future productivity. Indirect effects include altered feeding behavior, reduced feed intake, and heightened susceptibility to metabolic disorders, while rising temperatures also affect the distribution and prevalence of pathogens, disease vectors, parasites, and pasture pests, increasing disease incidence. Water scarcity and salinization further exacerbate health risks and impair metabolic and reproductive functions. Additionally, microbial contamination of milk, including pathogens, is intensified under heat stress and suboptimal hygiene, compromising milk safety and quality. Behavioral changes, including reduced overall activity, altered feeding patterns, and suppression of estrus signs, further undermine reproductive efficiency. Collectively, these findings underscore the urgent need for comprehensive adaptive strategies, encompassing improved management, biosecurity, nutrition, and welfare practices, to mitigate the multifaceted impacts of climate change on dairy production systems.

3.2.3. Impacts of Climate Change on Feed Availability and Cow Nutrition

As extreme weather events become increasingly frequent, ensuring a consistent supply of high-quality feed for dairy cows poses a growing challenge. Feed production and quality are expected to be significantly impacted by rising atmospheric CO_2 concentrations, elevated temperatures, and reduced water availability and distribution, factors that may vary considerably across different regions, production systems, and animal types [8]. The availability, quality, and quantity of forage are largely determined by geographic location, length of the growing season, and pasture condition [40].

Excessive heat can disrupt the growth patterns of feed crops and degrade the nutritional quality of forage, particularly affecting C4 plants that are prevalent in tropical climates. Although less than 1% of all terrestrial plants are C4 species, they are well-adapted to hotter environments and exhibit greater water-use efficiency compared to C3 plants [40]. A temperature increase from 30 °C to 35 °C may enhance herbage growth in C4 species; however, the magnitude and nature of these effects vary depending on the geographic region, production system, and plant species involved [40]. Furthermore, shifts in seasonal temperature, water availability, and atmospheric CO_2 concentrations can alter the competitive dynamics among pasture species by changing their optimal growth rates [40]. In continental climates, higher temperatures coupled with reduced precipitation have been associated with decreases in crude protein (CP) content and digestible organic matter in forage [48]. Additionally, heat stress and drought conditions cause fluctuations in nitrogen and water-soluble carbohydrate levels in feed crops. Elevated temperatures also increase lignin and cell wall content, which reduces forage digestibility and nutrient availability for dairy cattle [40].

Most grazing pastures consist of monoculture grasses, which are often vulnerable to droughts and flooding. Consequently, extreme climatic events are likely to reduce forage yields in the future, posing significant challenges in providing sufficient high-quality feed for dairy cows. This reduction may also increase production costs for farmers, who would need to purchase additional feed. Conversely, grassland management practices have the potential to influence the net carbon accumulation in grassland soils by enhancing the sequestration of atmospheric carbon dioxide. Adopting more circular and sustainable management approaches could not only improve resource-use efficiency but also contribute to mitigating climate change [49]. Moreover, the nutritional composition of milk is closely linked to changes in feed quality and availability, which fluctuate with climatic conditions. For instance, cattle grazing on low-quality pastures during drought periods typically experience reduced dry matter intake, resulting in decreased milk protein and casein yields [50]. Additionally, under heat stress conditions, deficiencies in sodium and potassium can induce metabolic alkalosis in dairy calves, leading to increased respiration rates [40].

Climate change significantly threatens the availability, quality, and nutritional value of feed for dairy cattle, as rising temperatures, elevated CO_2 levels, and altered precipitation patterns increasingly disrupt forage production. Extreme heat and drought negatively affect the growth, protein content, and digestibility of pasture plants, particularly monoculture grasses and C4 species, which are otherwise adapted to warmer climates. Seasonal and regional variations further influence forage yield and nutrient composition, while increased lignin and cell wall content under heat stress reduces feed digestibility. These challenges directly impact cow nutrition, decreasing dry matter intake and lowering milk protein and casein production. Additionally, imbalances in key minerals such as sodium and potassium under heat stress can induce metabolic disorders, including alkalosis, compromising animal health and productivity. The anticipated reduction in forage availability may also escalate feed costs, placing economic pressure on farmers. Conversely, adopting sustainable grassland management and resource-efficient practices can mitigate these effects, enhance carbon sequestration, and improve feed resilience. Overall, climate-driven disruptions in feed supply represent a critical constraint on dairy production, affecting both animal nutrition and milk quality, highlighting the urgent need for adaptive strategies to safeguard herd health and productivity under changing environmental conditions.

3.3. Economic Impact of Climate Change on Milk Production

Differences in economic loss estimates are largely attributed to the size of the dairy industry in each country, the methodologies used to assess impact, and varying environmental conditions such as the number of days exceeding thermal comfort thresholds [51]. Milk production losses were found to vary by geographical location, emphasizing the importance of selecting production sites with more favorable climatic conditions. Further research is needed to conduct cost-benefit analyses comparing investments in livestock heat mitigation with potential production losses due to climate change. Such studies are essential for identifying effective adaptation strategies to minimize economic impact [52].

In recent years, unprecedented climatic fluctuations, such as sustained increases in temperature and humidity, heat waves, and solar flares, have resulted in economic losses amounting to billions of dollars in both the dairy and meat industries. It is estimated that by the year 2050, the U.S. dairy sector alone will incur losses exceeding $1.7 billion [53]. However, milk production reached its lowest point in August at 30.88 kg/day, coinciding with the peak in THI. This trend suggests that heat stress begins to adversely affect milk yield once a certain THI threshold is exceeded. In contrast, milk production peaked in May at 32.41 kg/day, when environmental conditions were more moderate. A noticeable decline in yield began in June as THI levels rose, culminating in the lowest output in August, followed by a gradual recovery in September. Economically, this decline in production was reflected in daily milk revenue, which dropped to $24.16 USD/day in August—a decrease of $1.40 USD/day or 5.5% compared to May. If such reductions persist, they could result in substantial financial losses for dairy farmers, highlighting the direct economic impact of heat stress [54].

Moreover, Campos et al., assuming a THI threshold of 58 for fat and protein yields, cows experience heat stress for an average of 156 days per year, with an average THI exceeding the threshold by 10 units. Considering the average decline per unit of THI above the threshold across lactations and provinces, the overall reductions in fat and protein yields were estimated at 2.98 kg and 3.79 kg per cow per year, respectively. Based on average prices paid to producers—$8.28/kg for butterfat and $6.38/kg for protein, the impact translates to a potential economic loss of $50.40 per cow annually. This represents approximately 1% of the total income per cow per year, based on the average annual production of 426.5 kg of fat and 354 kg of protein. With 222,129 cows in Ontario and 247,166 in Quebec, annual losses in these provinces could reach $34.5 million [51].

In the United States, St-Pierre et al. estimated average annual economic losses due to heat stress ranging from $897 million to $1.5 billion [55]. Other studies have estimated annual losses associated with reduced milk yield when dry cows are not cooled at $87 per cow [56], and losses of daughters born from dams exposed to heat stress during late gestation at $39 per daughter [57]. Additionally, Hempel et al. concluded that by 2050, heat stress events, defined as hours when THI ≥ 72, will significantly increase in Mediterranean regions compared to Central Europe, with up to 500 additional events projected under a pessimistic scenario [58]. Central Europe, by contrast, may experience about 50 additional events. Heat stress risks are expected not only in summer but also in spring and autumn in the Mediterranean [52].

Fodor et al. projected similar impacts in the United Kingdom. Both studies forecast a decline in milk yield at THI = 68: a reduction of up to 2.8% in Europe and 2.4% in the Atlantic region [59]. Rising temperatures may also affect milk quality and somatic cell counts, though more detailed studies are needed [60]. Moreover, in South Africa's semi-arid regions, heat stress was found to reduce both milk quantity and quality. Using 2014–2016 milk prices, Ogundeji et al. estimated losses under a THI threshold of 70 at $0.0094 per cow per day (about $483 annually per farm). When the threshold was reduced to 65, losses rose to $0.0705 per cow per day (about $3605 per year for a 140-cow herd). Without adaptation strategies, production losses are expected to double by mid-century. However, moderate mitigation measures (e.g., wetting, forced ventilation) yielded positive results. Strong polynomial correlations (R^2 = 0.73–0.79) showed milk losses rising sharply when maximum temperatures exceeded 25 °C [52].

In Chile, both THI and Adjusted THI (THIa) were used to measure heat stress, which includes solar radiation and wind speed. Results showed that milk production losses increased significantly when solar radiation and wind were considered. Estimated economic losses ranged from $91.5 to $184.2 per cow during summer, with national losses between $29 million and $108 million annually [61]. Additionally, Casarotto et al.,found that daughters of heat-stressed cows have a lower survival rate until first calving (71% vs. 83%), increasing the cost of raising a heifer by $157.50. Considering state-level heat stress days, average U.S. dairy farms face an extra heifer rearing cost of $14.30 per cow per year. In Florida, this cost reaches $47.30 per cow, totaling $5.7 million annually. Nationally, extra heifer rearing costs amount to $134 million annually. Additionally, reduced productive lifespan due to heat stress leads to further losses of $9.61 per cow annually, potentially reaching $90 million nationally if dry cows are not cooled [62].

On the other hand, severe climatic fluctuations, including rising temperatures, humidity, and heat waves, exacerbate heat stress in agricultural animals, particularly dairy cattle, resulting in significant economic losses in milk and meat production. Heat stress leads to reduced milk yield, increased mortality rates, decreased fertility, and higher rearing costs, with adverse effects typically beginning once the Temperature-Humidity Index (THI) surpasses a critical threshold. The severity of these impacts varies across regions and production systems, with hotter and more vulnerable areas facing greater challenges compared to moderate climates. Studies predict an increase in the frequency and duration of heat stress events in the coming decades, intensifying the negative effects on productivity and animal welfare. These reductions in yield, along with declines in milk quality and increased rearing expenses, translate into substantial financial losses at both farm and national levels, losses that could potentially double without effective adaptation measures. Therefore, it is imperative to implement diverse mitigation strategies—such as improving housing conditions, employing cooling technologies, and breeding heat-tolerant livestock—to ensure sustainable production and maintain profitability within the livestock sector.

Climate change, particularly rising temperatures, increased humidity, and frequent heat waves, exerts profound economic effects on milk production by reducing yield, impairing milk quality, and increasing operational costs. Heat stress negatively impacts cow productivity once THI exceeds critical thresholds, causing declines in milk fat and protein, shorter lactation periods, and higher mortality rates, while also increasing rearing expenses for replacement heifers. The magnitude of economic losses varies by region, herd size, and production system, with hotter and more vulnerable areas experiencing the most severe impacts. Projections indicate that, without effective adaptation, these losses could double by mid-century, threatening both farm-level profitability and national dairy economies. Conversely, moderate mitigation strategies—such as improved housing, ventilation, cooling systems, and selective breeding for heat-tolerant livestock—have been shown to reduce production losses and associated costs. Overall, implementing comprehensive adaptation measures is essential to sustain milk production, protect dairy farm incomes, and ensure long-term economic resilience in the livestock sector under increasingly challenging climatic conditions.

3.4. Global Dairy Industry Adopts Innovative Strategies to Combat Climate Change

The increasing global awareness of the profound impacts of climate change necessitates the development of robust, evidence-based strategies to both mitigate future risks and address current challenges arising from dynamic environmental changes. In the context of agriculture and livestock production, this imperative calls for a transition toward more sustainable and resilient systems capable of adapting to climate change. Effective adaptation strategies should be grounded in systematic climate monitoring and employ a multifaceted approach that includes improved animal husbandry practices, utilization of advanced diagnostic technologies, innovative disease control methods, sustainable pharmaceutical use, and the strategic integration of emerging preventive measures. This study aims to critically evaluate these strategies, emphasizing the importance of region-specific solutions informed by comprehensive data on climate trends, local environmental characteristics, and pathogen distributions. Such an approach will contribute to the advancement of sustainable livestock production amid evolving environmental conditions.

3.4.1. Genetics and Breeding Programs

It is well established that factors such as breed, age, stage of lactation, parity, and milking frequency significantly influence dairy cattle performance. Therefore, the implementation of selection and genetic improvement programs can enhance the productivity and profitability of local cattle breeds [63]. Although future production levels are anticipated to rise due to genetic advancements, climate change poses a threat by increasing heat stress and associated adaptation costs, potentially undermining these gains [64]. Moreover, genetic selection aimed at higher milk yields has been linked to reduced heat tolerance in dairy cows, indicating that continued selection for production traits could exacerbate the negative effects of global warming [65].

To overcome the limitations of adaptation strategies that focus only on the short-term effects of heat stress, genetic adaptation of dairy cattle, incorporating resilience to thermal load as a functional trait in breeding programs, can serve as a sustainable long-term solution. Traits such as stable rectal temperature and hair coat color are potential indicators of heat tolerance [66]. While phenotyping for resource use efficiency traits is challenging and costly, genomic selection offers a promising approach to identify and breed the most productive and resilient animals. The application of new technologies, including genetic breeding and advanced reproductive techniques, is expected to play a crucial role in mitigating climate-related challenges in the livestock sector. Genetic improvement is recognized as a particularly cost-effective technology that produces permanent, beneficial changes in ruminants. Key genomic traits associated with productive efficiency include dry matter intake (DMI), residual feed intake (RFI), and methane emissions, all of which can be effectively incorporated into breeding programs [1]. Moreover, the accuracy of genomic predictions for RFI, energy balance, and DMI in farm animals ranges from 0.20 to 0.43 [67].

On the other hand, heat-tolerant animals possess a greater capacity to maintain their core body temperature under changing climatic conditions [8]. Certain breeds are capable of producing higher levels of specific heat shock proteins (HSPs), which play a key role in their adaptation mechanisms to heat stress [68]. Moreover, the performance of imported breeds tends to decline when exposed to hot environments compared to their native climates [69]. In contrast, local breeds often perform better under adverse climatic conditions such as high temperatures, drought, and limited feed and water availability, due to their robustness and superior genetic adaptation to the local environment. Therefore, conserving local breeds that are well adapted to regional environments can be economically beneficial while also safeguarding natural resources for future generations [70]. Furthermore, native cattle breeds offer farmers diversified income opportunities and serve as a vital element in agricultural diversification strategies [5]. In addition, breeding for more productive animals can reduce the nutrient requirements needed to achieve the same production levels. This can be accomplished through genetic improvements in daily weight gain and feed conversion efficiency, making it a valuable strategy for mitigating greenhouse gas emissions. However, the introduction of new breeds and crossbreeds that significantly reduce greenhouse gases must be carefully aligned with existing production systems and climatic conditions, which are often constrained by limited resources. Additionally, improved fertility in dairy cattle has been shown to reduce methane emissions by 10–24% and nitrous oxide emissions by 9–17% [71].

3.4.2. Nutrition and Feeding Management

Adaptation of grassland plant species through targeted cultivation and management strategies offers essential options to mitigate the impacts of climate change on feed production [71]. Grazing management practices that enhance carbon sequestration include maintaining pastureland carrying capacity by employing rotational grazing, optimizing stocking rates, and avoiding livestock grazing on degraded pastures [40]. Additionally, implementing appropriate feeding management strategies that consider climatic factors is crucial to reduce the negative impacts of heat stress on the dietary supply for dairy cattle, ensuring optimal performance, such as milk yield and fertility, while also improving dietary digestibility for ruminants [8]. Nutritional approaches during heat stress may include adjustments in dietary composition, such as increasing dietary fiber and fat, supplementation with microbial additives, vitamins, and other anti-stress compounds. For example, supplementing high-yielding cows with vitamins and increasing the energy density of rations through saturated fatty acid supplementation can help improve the animals' ability to cope with heat stress by reducing their body temperature [72]. Dietary fiber and fat are recognized as readily available nutrients that alleviate the adverse effects of heat stress in animals [73]. However, at high ambient temperatures, animals expend considerable feed energy through panting and sweating, which are natural cooling mechanisms via evaporation [19].

On the other hand, dietary manipulation offers several viable strategies to mitigate the effects of climate change by reducing greenhouse gas (GHG) emissions from the livestock sector [1]. Increasing starch in the diet promotes higher propionate concentrations relative to acetate, which helps reduce hydrogen availability for CH_4 production and lowers rumen pH, thereby inhibiting methanogenesis [74]. Additionally, supplementing animal rations with vegetable and animal lipids is widely used to enhance productivity while reducing methane emissions by approximately 4–5% for every 1% increase in dietary lipid content. However, lipid supplementation should not exceed 7%, as oversupply can reduce feed intake, impair digestion, negatively affect productive functions, and result in lower milk production [75]. Supplementing ruminant diets with dietary oils can improve milk and meat production efficiency and reduce GHG emissions [1]. Specifically, soybean oil, canola oil, and coconut oil are commonly used to control methane production, achieving reductions of 19–62% in various ruminants [76]. Moreover, sunflower oil in animal rations has been shown to reduce rumen fermentation by 11.5–22% [77]. Moreover, supplying ruminant diets with concentrates has been shown to have a negative correlation with methanogenesis in animals [78]. Additionally, supplementing rations with ionophores, which are used to improve milk production, can also reduce CH_4 emissions [79]. Forages naturally contain several plant secondary metabolites, such as tannins, saponins, and phenolic monomers, which are toxic to certain rumen microbes, reducing enteric fermentation and methanogenesis in ruminants [80]. Furthermore, several chemical compounds, including chloral hydrate, amichloral, bromochloromethane, nitroethane, and 2-nitropropanol, have been identified as effective inhibitors of methane production in ruminant animals [1].

3.4.3. Management System and Hygiene

Ensuring the immediate well-being of the herd requires well-designed housing and strategic management practices focused on maintaining cooler temperatures. This includes ventilation systems and shaded areas that help reduce ambient heat, thereby minimizing heat stress in the animals [40]. Various husbandry and management options are available to mitigate heat stress, such as cooling techniques including fans, misters, sprinklers, cooled waterbeds, and tunnel ventilation[81]. Multiple studies have demonstrated that a combined approach of shade and sprinklers is more effective at reducing respiration rates than either shade or sprinklers alone. Moreover, providing adequate shade is an economical and easily accessible method to alleviate the adverse effects of heat stress by preventing direct exposure to solar radiation[82]. Additionally, cooling management has positive effects on ovarian function, estrus cycle length, and overall fertility in dairy cattle exposed to heat stress[8].

The choice of manure management and housing systems significantly influences greenhouse gas emissions. Animal housing and manure storage in deep litter systems tend to produce higher N_2O emissions compared to the more anaerobic slurry-based systems; therefore, managing slurry-based systems can help reduce N_2O emissions[83]. Additionally, nutrient recovery technologies, such as anaerobic digestion, break down manure to produce nutrient-rich products that can replace synthetic fertilizers. This approach has grown significantly in the past decade and helps mitigate CO_2 and N_2O emissions associated with synthetic fertilizer production[49]. In line with this, integrated crop-livestock systems (ICLS) are considered sustainable agricultural models that can enhance food security while addressing climate change challenges[1].

To protect livestock health, the development and implementation of a robust biosecurity strategy on dairy farms is essential. Biosecurity encompasses simple, everyday practices designed to reduce the risk of diseases, weeds, or pests entering, spreading within, or leaving the farm, thereby minimizing financial losses and maintaining market access. For long-term success, the dairy industry must prepare for the broad impacts of climate change on animal health, increased vulnerability to diseases, and the resulting effects on mortality and immunity. Moreover, advanced disease surveillance, combined with technological innovations such as DNA fingerprinting, genome sequencing, resistance testing, antiviral treatments, and strategic crossbreeding, may help prevent or mitigate the spread of emerging diseases. It is important to note that the introduction and mixing of new genetic material, as well as disease transmission between humans and livestock, could lead to the emergence of novel diseases[40].

3.4.4. Education and Awareness

Providing technical support and educational training to farmers is a fundamental pillar in enhancing the dairy sector's resilience to the challenges posed by climate change. Farmers, especially small-scale producers and rural communities, require the necessary knowledge and tools to understand the impacts of climate change on the health and productivity of dairy cattle, as well as on the sustainability of their natural resources. Support and training programs include specialized courses aimed at raising farmers' awareness of the latest sustainable practices in dairy farm management, such as the implementation of efficient cooling technologies to alleviate heat stress, improving feeding regimes to meet the changing nutritional needs of animals during hot and dry periods, and better management of water and feed resources amidst their limited availability due to climate change. Furthermore, these educational programs provide guidance on utilizing modern technologies to monitor cattle health and enhance productivity, including heat and humidity sensors and smart ventilation systems, which facilitate more precise and effective decision-making. Workshops and awareness seminars also play a vital role in building communication networks between farmers and agricultural experts, fostering the exchange of experiences and continuous updates on scientific knowledge related to climate and its effects on livestock production. Through these initiatives, farmers are empowered to implement better adaptation and risk mitigation strategies, contributing to greater stability in milk production and ensuring food security at both local and global levels.

3.4.5. Artificial Intelligence and Precision Climate Forecasting

Artificial intelligence and big data analytics represent innovative tools to enhance dairy farmers' ability to adapt to rapidly changing climatic conditions. By collecting and analyzing vast amounts of climatic, environmental, and animal behavior data, highly accurate predictive models can be developed to forecast extreme heat events, fluctuations in humidity, and the spread of livestock diseases. These models enable farmers to proactively plan cow nutrition, manage water usage, and optimize housing conditions to provide a more comfortable environment for the herd, thereby reducing heat stress and improving milk productivity. Furthermore, these predictive systems can be integrated with real-time monitoring technologies to deliver early warnings about climate-related risks, enhancing proactive decision-making, minimizing economic losses associated with extreme weather events, and ensuring sustainable productivity amid ongoing environmental changes.

3.4.6. Animal Biometric Monitoring

Animal biometric monitoring employs advanced sensor technologies to continuously track vital physiological and behavioral indicators in dairy cows, including body temperature, respiration rate, and thermoregulatory behaviors. These real-time data streams allow for the immediate detection of early signs of heat stress or other environmental challenges, enabling farmers to implement preventive interventions before the animal's well-being or productivity is compromised. Alerts generated by these monitoring systems can prompt timely actions such as adjusting feed composition, enhancing cooling strategies, providing shade, or modifying water availability. By integrating biometric monitoring into daily farm management, producers can optimize herd health, improve milk yield, and reduce losses associated with thermal stress, while also supporting precision livestock farming practices that maximize both animal welfare and operational efficiency.

4. Conclusions

Severe climatic changes have already exerted substantial direct and indirect impacts on livestock production, particularly within the dairy sector. These changes negatively affect the availability and quality of feed and water, as well as animal health and overall performance, leading to higher mortality rates, weakened immune responses, increased transmission of infectious diseases, disrupted growth and reproductive functions, altered feed intake, and reduced milk yield, especially among high-producing dairy cattle, resulting in significant economic losses. This study provides a comprehensive analysis of both the direct and indirect effects of severe climatic changes, highlighting the mechanisms that link these challenges to practical strategies for sustainable adaptation. Unlike previous reviews that primarily described the general impacts of climate change, this paper offers novel contributions by presenting an analytical framework connecting animal health, productivity, and the efficiency of genetic resources, with a focus on developing heat-tolerant breeds and preserving locally adapted breeds. Furthermore, the study provides actionable recommendations to enhance sustainability and reduce carbon footprints, while integrating educational and training dimensions to strengthen the professional competence of livestock management specialists. In doing so, the paper presents a comprehensive and innovative perspective for addressing climatic challenges and achieving sustainable and effective management of animal resources in the future.

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Data Availability

The data used for this study is available upon request from the author.

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Conflicts of Interest

The author disclosed no conflict of interest.

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