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Invited Review Article

Impacts of climate variability and extreme weather conditions on animal husbandry in India: Challenges and strategies

D. Banerjee[1*], J. Mukherjee[1], T. K. Das[2], P. K. Das[1], P. R. Ghosh[1] and K. Das[1]

[1]Department of Veterinary Physiology, West Bengal University of Animal and Fishery Sciences, Kolkata- 700 037, West Bengal, India; [2]Department of Instructional Livestock Farm Complex, College of Veterinary Sciences and A. H., R. K Nagar- 799 008, Agartala, Tripura, India

Abstract

Climate variability and extreme weather events profoundly affect animal growth, productivity, and economic viability in India. Maintaining homeothermy and homeostasis is critical for animal survival and reproduction. However, even within suitable temperature ranges, substantial energy is diverted to thermoregulation, limiting genetic production potential. Since 1993, India's annual mean temperatures have consistently exceeded normal levels, revealing a warming trend. Elevated temperatures and humidity reduce body weight gain, productivity and disrupt physiological functions in livestock. Extreme events like floods and droughts further threaten India's livestock sector. This sector is a significant greenhouse gas emitter, exacerbating climate change impacts and thermal stress on animals. Climate change poses multifaceted challenges to livestock, affecting production and farmers' livelihoods. Hot and dry weather severely impacts water availability, forage quality, and animal health. Animals' ability to adapt to thermal stress varies by species and breed. Climate change and global warming notably affect milk quantity and quality, especially among indigenous cattle, crossbred cattle, and buffaloes. Altered reproductive functions are documented during heat stress in animals and birds. Increased maximum temperature reduces the feed intake of animals. Global warming may alter the prevalence and spread of animal diseases, particularly those transmitted by vector-borne pests. Effective adaptation and mitigation strategies are vital to address the detrimental effects of climate change on livestock. These strategies reduce risks while promoting sustainable development in the sector. In summary, this review discusses the impacts of climate change on Indian livestock, emphasizing the urgent need for adaptive and mitigative measures to ensure livestock resilience and sustainability in the face of ongoing climate challenges.

Keywords: Adaptation, Climate variability, Livestock, Mitigation, Thermal stress

Highlights

- Climate variability and extreme weather events profoundly affect animal growth, productivity and economic viability.
- Elevated temperatures and humidity lowers productivity and disrupt physiological functions in livestock.
- Global warming may alter the prevalence and spread of animal diseases.
- Effective adaptation and mitigation strategies are vital to address climate change's detrimental effects on livestock.

INTRODUCTION

The Indian agricultural system heavily relies on small and marginal farmers (Satyasai *et al.*, 2022), who practice crop-livestock integrated farming, encompassing a significant number of ruminants and non-ruminants (Devendra *et al.*, 1997). Large animals play an integral role in agriculture, contributing significantly in terms of milk, meat, and draught power (Sekaran *et al.*, 2021). India's livestock sector stands as one of the largest in the world, a cornerstone of the nation's economic landscape. As of 2022-23, agriculture and its allied sectors contribute nearly 18.3 percent to India's GDP (Press Information Bureaupib.gov.in). India boasts abundant livestock resources with the livestock sector contributing 4.11 percent to the GDP and a substantial 25.6 percent of the total Agriculture GDP (Venkateshwarlu, 2021). The intricate relationship between environmental factors and animal production and health is well-established. Climate variability and extreme weather conditions wield a profound influence on animal growth, productivity and the economic efficiency of animal husbandry practices (Kargbo *et al.*, 2023). To ensure survival, production, and reproduction, animals must maintain homeothermy and homeostasis (El-Tarabany *et al.*, 2017). However, even within the range of environmental temperatures suitable for

*Corresponding Author, E-Mail: dipakndri@gmail.com

homeothermy, energy is expended on thermoregulatory mechanisms, limiting animals from achieving their full genetic production potential which can be expressed optimally within a narrower range of environmental temperature known as the "zone of thermo-neutrality" where metabolic rate remains independent of external temperature fluctuations (Bhardwaj, 2022). Environmental temperature emerges as the most significant climatic factor, followed by humidity, radiation, and wind velocity, which imposes stress and directly impacts livestock production (Cheng *et al.*, 2022).

Changing climate patterns in India

The climate change scenario in India has witnessed significant shifts over the years. From 1901 to 2005, the annual mean temperature for the entire country increased by 0.51°C (Kothawale and Rupa Kumar, 2005; Rupa Kumar *et al.*, 2006). Notably, since 1993, the annual mean temperature consistently exceeded normal levels (Power *et al.*, 2017). The primary contributor to this warming trend is the increase in maximum temperatures across the nation. However, since 1990, there has also been a steady rise in minimum temperature, with the rate of increase slightly surpassing that of maximum temperatures (Sanjay *et al.*, 2020).

A spatial analysis of mean annual temperatures reveals significant positive trends in most parts of the country, indicating a consistent warming pattern (Sabin *et al.*, 2020). However, certain regions such as Rajasthan, Gujarat and Bihar, exhibit significant negative trends, suggesting localized cooling (Ray *et al.*, 2020). Season-wise temperature changes show that the most substantial rise in mean temperature occurred during the post-monsoon season (0.7°C), followed by the winter season (0.67°C), pre-monsoon season (0.50°C) and monsoon season (0.30°C). Notably, during the winter season since 1991, minimum temperatures have risen appreciably, particularly over the northern plains, leading to frequent occurrences of fog (Shabudeen, 2011).

In the lower troposphere, upper air temperatures have displayed a significant increasing trend, notably at the 850 hectopascal (hPa) level (Desinayak *et al.*, 2023). Conversely, the upper troposphere has exhibited a decreasing trend, although it is not statistically significant. While all India summer monsoon season (June to September) and the rainfall for all four monsoon months do not show significant trends as there are notable regional variations (Ghosh *et al.*,2009). India's reliance on the summer monsoon, which accounts for 70-80 percent of annual rainfall, exposes the country to droughts and floods in different agro-climatic zones between June and September. Over the past century, India has experienced eighteen large-scale droughts, including notable occurrences in 1095, 1911, 1915, 1918, 1920, 1941, 1951, 1965, 1966, 1972, 1974, 1979, 1982, 1986, 1987, 1988, 1999 and 2000 (Gautam and Bana, 2014). These droughts can be attributed to the failure of rains from the southwest monsoon (Thapliyal, 1984). These observations highlight the complex and evolving climate dynamics in India, impacting various aspects of agriculture, including livestock farming.

Contribution of livestock sector to greenhouse gas emissions

The livestock sector plays a significant role in contributing to greenhouse gas (GHG) emissions in India (Chhabra *et al.*, 2013). Methane emissions from enteric fermentation, primarily from indigenous cattle, crossbred cattle, and buffaloes, have been estimated using the Tier 2 methodology of the Intergovernmental Panel on Climate Change (IPCC). For other animals such as sheep, goats, equines, pigs and miscellaneous species, the Tier 1 methodology of IPCC and default emission factors were employed. As of 2003, the total methane emissions resulting from enteric fermentation and manure management from the livestock population of approximately 485 million heads amounted to 9.37 teragrams per annum (Tg/annum) (Upadhyay *et al.*, 2007a, 2008a). The major contributors to methane emissions were indigenous cattle, crossbred cattle and buffaloes accounting for 40%, 8%, and 40% of the total emissions, respectively. Lactating animals, particularly buffaloes and cattle contributed 3.42 Tg, with lactating buffaloes alone contributing 2.04 Tg. Draught animals, crucial for agricultural work, emit approximately 1.2 Tg of methane per annum (Upadhyay *et al.*, 2008b).

On an average, a working bullock produces 40-50 grams of methane per day (Pathak *et al.*, 2013). Given their population size and annual emissions, their collective contribution to methane emissions is substantial. An analysis of draught animal contributions to farm power and global warming, attributed to enteric fermentation, in relation to production efficiency indicates that methane emissions from cattle and buffaloes amount to 90-100 grams per horsepower per day or 35-40 kilograms per annum for an average bullock (Pathak *et al.*, 2013). Male working buffaloes emit about 7-10 kilograms more methane per annum compared to indigenous bullocks (Pathak *et al.*, 2013). In the context of current and projected trends in GHG emissions from India and other selected countries, it's noteworthy that while Indian emissions grew at a rate of 4% per annum between 1990 and 2000 and are projected to increase further to meet national developmental needs, the absolute level of GHG emissions in 2020 is expected to remain below 5% of global emissions. Additionally, per capita emissions in India will still be relatively low compared to most developed countries and the global average (Sharma *et al.*, 2006).

Despite the low per capita emissions from the livestock sector in India, considering the multi-utility of Indian livestock for milk, meat and labor, it is essential to address the sizable population of non-descript cattle primarily maintained for draught power, given their methane emissions per head of livestock (Patra, 2014). This is especially pertinent in the context of climate change mitigation efforts.

Impact of climate change on livestock

The escalating effects of climate change are leading to a rise in thermal stress among livestock, posing challenges to animal productivity and well-being (Banerjee and Ashutosh, 2011). In the context of India, an analysis of THI levels during different parts of the year reveals the predominance of indigenous or non-descript animal breeds in regions with high THI. This can be attributed to the superior adaptive capacity of these breeds, enabling them to cope with feed scarcity and harsh environmental conditions more effectively (Banerjee *et al.*, 2014). In essence, as climate change continues to drive up temperatures and alter humidity patterns, understanding and managing thermal stress in livestock becomes a point of paramount significance (Banerjee and Ashutosh, 2011). This involves adopting strategies that mitigate the adverse effects of elevated THI such as improved shelter, ventilation, and breed selection to ensure the well-being and productivity of animals in a changing climate (Sejian *et al.*, 2018).

Climate change in India is having profound and multifaceted impacts on livestock, posing serious challenges to their well-being and the livelihoods of farmers (Sejian *et al.*, 2018). Rising temperatures and changing precipitation patterns are leading to inadequate vegetation and drying of water resources, particularly during the summer months, providing significant stress on livestock species. Prolonged periods of hot and dry weather severely impact water availability, the quality of forage and roughage and the production and reproduction characteristics and health status of animals (Rashamol *et al.*, 2019). Climate change is contributing to an increased number of stress days for livestock. Among all the domesticated production animals, dairy cows are most susceptible to heat stress as a result of the intensive long-term breeding done in them so as to improve their milk production, which has led to higher metabolic heat generation in these animals (Silpa *et al.*, 2021). Elevated temperatures and humidity levels can lead to reduced body weight gain, decreased productivity, and disruptions in various physiological functions. Livestock in India face vulnerability to extreme climate-induced events such as floods, droughts, and strong dust storms. Among these, floods and droughts are particularly devastating, causing substantial annual losses to farmers. Indeed, draught is one of the most serious problems arising from climate variability for human societies and ecosystems (Yurekli and Kurune, 2006). For example, more than 3,600 cattle died due to floods in 2002, and from 1953 to 2002, over 91,000 cattle deaths were recorded due to floods alone (Selvaraj, 2022). Changes in the pattern of rainfall and ranges of temperature affect feed availability, and weed, pest and disease incidence. The hot and hot-humid conditions prevailing from April to October in most agroclimatic zones of India adversely affect livestock productivity. Direct solar exposure and thermal heat load during summer make livestock more vulnerable to stress.

Impact of climate change on milk production

Climate change and global warming have significant implications for milk production in India, particularly affecting indigenous cattle, crossbred cattle, and buffaloes. Temperature variations and the rise in temperatures are key factors impacting livestock functions and milk production.

Lactating cows have high metabolic demands owing to a higher rate of heat dissipation (West *et al.*, 2003), and exposure to heat stress affects this heat dissipation process, making the animal susceptible to heat stress (Pragna *et al.*, 2017). Climate change and global warming have significant implications on milk quantity and quality, particularly affecting indigenous cattle, crossbred cattle, and buffaloes (Sreenivasaiah, 2016) by reducing their feed intake (Pragna *et al.*, 2017; Summer *et al.*, 2019). The estimated reduction of milk production due to heat stress is 40–50%, however artificial cooling management can decrease this reduction up to 10–15% (Silpa *et al.*, 2021). In India, the annual milk loss due to heat stress was estimated to be 1.8MT accounting 0.38 billion USD (Upadhyay, 2010). Along with reduction in the quantity of milk production, heat stress caused a significant decrease in casein percentage (Bernabucci *et al.*, 2002) and triacylglycerol and polar lipid profiles (Liu *et al.*, 2017). The mammary immunity was also compromised during heat stress along with higher somatic cell counts (Mukherjee *et al.*, 2015). According to the climate change models, the mean global temperature may be 2.6-4.8°C warmer by 2100 as compared to the conditions that prevailed in 2010, which is expected to have adverse effects on physiological functions like milk production and reproduction (IPCC, 2014). This severe temperature rise is predicted to negatively impact total milk production in India, with an estimated reduction of about 3.2 million tons in 2020 and over 15 million tons in 2050 (Das *et al.*, 2016). Northern India is anticipated to experience a more pronounced negative impact on milk production for both cattle and buffaloes due to rising temperatures, especially during the periods 2040-2069 and 2070-2099 (Singh and Upadhyay, 2009). Sudden temperature changes, such as a rise in maximum temperature (heat wave) during summer or a fall in minimum temperature (cold wave) during winter, lead to declines in milk yield. These events can result in yield reductions ranging from 10-30% in the first lactation and 5-20% in subsequent lactations. The extent of the decline is typically less during mid-lactation compared to early or late stages. Global warming, leading to increased stressful days with Temperature Humidity Index (THI) values exceeding 80 and a higher frequency of warm days, will further impact cattle and buffalo milk yield (Upadhyay, 2007b).

Impact of climate change on animal reproduction

Several literatures documented the altered reproductive functions in both males and females during heat stress in ruminants (Collier *et al.*, 1982; Gwazdauskas, 1985; Cheng *et al.*, 2022), pigs (Ross *et al.*, 2017) and poultry (Nawab *et al.*, 2018). In females, heat stress severely affects fertility (De Rensis *et al.*, 2003), quality of oocyte (Ronchi *et al.*, 2001; Barati *et al.*, 2008;), embryo development and pregnancy (Wolfenson *et al.*, 2000; Hansen *et al.*, 2007). In males, heat stress causes lower sperm quality and quantity (Karaca *et al.*, 2002; Kunavongkrita *et al.*, 2005). This prolonged period of stress impacts reproductive rhythms (Sakatani *et al.*, 2012). Estrus behavior in livestock exhibits diurnal patterns with some species showing heat symptoms during specific parts of the day. For example, domestic buffaloes of the Murrah breed exhibit estrus signs between 6 pm and 6 am with about 60% of them expressing estrus between 10 pm and 6 am (Madan and Prakash, 2007). Climate change, which leads to rising temperatures and increased radiant heat load, is likely to disrupt the reproductive rhythm through the pineal-hypothalamo-hypophyseal-gonadal axis (Kebede, 2016). Heat stress (HS) diminishes oocyte development by impeding both its growth and maturation (Singh *et al.*, 2013). During the summer months, a noticeable decrease of approximately 20-27% in conception rates (Chebel *et al.*, 2004), as well as a decline in the 90-day non-return rate to the first service among lactating dairy cows was also observed (Al-Katanani *et al.*, 1999). Heat stress (HS) adversely affects fertility by reducing the quality of oocytes and embryos through both direct and indirect mechanisms (Lacerda and Loureiro, 2015).

Impact of heat stress on livestock physiology

The physiological functions of animals are significantly influenced by temperature and humidity levels, and their ability to adapt to thermal stress varies among species and breeds (Banerjee *et al.*, 2014). The metabolism of livestock species is directly affected by ambient temperature rise and humidity levels. The magnitude of this response depends on the species, breed, and environmental factors. For instance, zebu cattle maintain a lower body temperature compared to crossbreeds, indicating differences in their metabolic responses to heat. Livestock utilize various mechanisms to maintain their body temperature, including radiation, conduction, convection, and evaporation. Sweat gland distribution, skin vascular blood dispersion capacity, and adrenergic mechanisms governing sweating rates play significant roles in heat dissipation (Dowling, 1955; Macfarlane, 1981). Zebu breeds, known for their heat tolerance, have a higher number of sweat glands and produce more sweat, allowing them to maintain lower body temperatures (Aggarwal and Upadhyay, 1997; Hansen, 2004). This efficient heat loss mechanism is crucial for their adaptability to tropical climates. Indian livestock breeds, particularly zebu cattle, have evolved to withstand thermal stress, limited feed and water availability, diseases and parasite loads. They excel in multiple dimensions of use, making them resilient to environmental and climatic stressors. Various adaptive mechanisms in livestock include coat color, hair coat length, skin pigmentation, sweat gland density and secretion rates. Additionally, their small body size, low energy requirements and the ability to utilize poor-quality feeds contribute to their efficiency in converting feed into energy. At the cellular level, genetic adaptations to resist deleterious effects of elevated temperature result in pre-implantation embryos from zebu being less likely to be inhibited in development by elevated temperature than are embryos from European breeds (Hansen, 2004). Studies on Sahiwal cattle have revealed their ability to withstand extra environmental heat loads by increasing skin evaporative losses (Aggarwal and Upadhyay, 1997). In contrast, Sahiwal-Holstein crossbreds struggle to dissipate extra heat, resulting in elevated body temperatures and distress symptoms. Temperature rise during summers, combined with solar radiation exposure, exacerbates thermal stress on crossbred cattle more than zebu breeds (Banerjee and Ashutosh, 2011). Thermal stresses trigger complex gene expression and biochemical adaptive responses. Heat shock proteins (HSPs) play crucial roles in environmental stress tolerance and thermal adaptation (Sørensen *et al.*, 2003; Banerjee *et al.*, 2014; Parkunan *et al.*, 2015; Archana *et al.*, 2017). These proteins are highly conserved across species and represent a significant portion of cellular proteins expressed in response to environmental stress (Banerjee *et al.*, 2014). The temperature and humidity levels have profound effects on livestock physiology, and various species and breeds have evolved unique mechanisms to cope with thermal stress (Banerjee *et al.*, 2015). Altered physio-biochemical, endocrine and behavioural changes were documented during heat stress in several species (Gogoi *et al.*, 2016; Parkunan *et al.*, 2019; Reddy *et al.*, 2021), which were used to evaluate stress in animals. Understanding these adaptations is essential for the development of strategies to improve livestock resilience in changing climatic conditions (Banerjee *et al.*, 2014).

Effect of temperature change on feed intake

Temperature changes, particularly increases in maximum temperature (Tmax) during the summer and rainy seasons, have a significant impact on the feed intake of animals (Hill and Wall, 2017). Crossbred animals are more sensitive to rising temperatures, especially during the summer and rainy seasons (Das *et al.*, 2016). These temperature increases affect their dry matter intake, which is a critical factor for their nutrition and productivity (Hill and Wall, 2017). Dry matter intake tends to decline with the rise in T_{max}, average temperature (Tav), and Temperature Humidity Index (THI) during the hot summer and hot-humid rainy seasons. This reduction in feed intake is a response to the thermal stress imposed by high temperatures and humidity. Conversely, during the winter season, dry matter intake increases as T_{min} (minimum temperature) declines. Cattle and buffaloes tend to consume more feed to meet their energy requirements and maintain body temperature in colder conditions. The rise in temperatures due to global warming, particularly during the summer and rainy seasons, is expected to have adverse effects on the feed intake of animals (Podder *et al.*, 2022). This reduction in feed intake can lead to decreased milk yield and overall production in lactating animals (Das *et al.*, 2016).

Impact of global warming on animal diseases

Global warming and the associated rise in temperature can have significant consequences on the prevalence and spread of animal diseases, especially those transmitted by vector-borne pests such as midges, flies, ticks and mosquitoes (Thornton *et al.*, 2009). Elevated temperatures and humidity levels are conducive to the proliferation and expansion of insects and disease vectors. This in tern has the potential to increase the geographic spread of vector-borne diseases such as bluetongue, lumpy skin diseases (LSDs), anaplasmosis, babesiosis, and theileriosis. This can lead to a higher population of disease-carrying organisms and thereby increasing the risk of disease transmission to livestock. Protozoan diseases such as trypanosomiasis and babesiosis are likely to become more prevalent, particularly in high-producing crossbred cattle. The IPCC (2007) report warned that global climate change patterns could positively affect the spatial distribution of vectors such as mosquitoes and ticks. The warmer climate may create conditions favorable for the survival and transmission of these diseases, potentially leading to higher infection rates. Some viral diseases, including diseases similar to Peste des Petits Ruminants (PPR) or Rinderpest (RP) may reappear and affect both small and large ruminant populations. A model simulated by Wittmann *et al.* (2001) demonstrated that an increase of 2°C of environmental temperature can extensively spread *Culicoides imicola*, which is responsible for the transmission of bluetongue virus in sheep, cattle, goats, and also wild ruminants. The increased temperature and altered climatic conditions can facilitate the spread of these viral diseases among susceptible livestock. Livestock, particularly high-producing animals like crossbred cows, may experience an increase in the frequency and incidence of diseases like mastitis and foot and mouth diseases (FMD). The rise in the number of stressful days, coupled with favorable climatic conditions for disease-causing organisms, can contribute to the spread of these ailments. Temperature rise can extend the seasons during which disease-causing organisms thrive. This can lead to diseases spreading in seasons or regions where they were previously less common, posing a challenge for disease control efforts. As the climate becomes more favorable for disease vectors and causative organisms, the geographical areas where these diseases are prevalent may expand. This expansion can affect both livestock and wildlife populations. The global warming and temperature increases can alter the dynamics of animal diseases by creating conditions that favor disease vectors and the growth of causative organisms.

Adaptation and mitigation strategies for climate-resilient livestock farming

Adaptation and mitigation are essential strategies for addressing the detrimental effects of climate change on livestock production (Cheng *et al.*, 2022). These strategies are complementary and serve to reduce and manage the risks associated with climate change while promoting sustainable development and equity. Climate change adaptation refers to adjustments made in ecological, social, or economic systems to either reduce the negative impacts or enhance the positive impacts of climate change (Smit and Olga, 2003). It can involve natural adaptations by animals to changing climate conditions or human interventions and practices aimed at helping animals adapt and improve their performance.

Animal responses: Natural adaptations that occur in animals as they respond to changing climatic conditions. Animals may adjust their behaviors, physiology and metabolism to cope with temperature variations, humidity levels, and other climate-related factors (Sejian *et al.*, 2018).

Management actions: Human interventions and management practices can significantly contribute to climate change adaptation in livestock (Rojas-Downing *et al.*, 2017). Some key management actions include:

Feeding management- By modifying nutritional management to reduce the internal heat load on animals. A common strategy is to increase the energy and nutrient densities of the diet by increasing concentrates, supplementing fat, reducing the fiber content of the diet and providing rumen undegradable protein (bypass protein) is thought to improve the cow's thermal balance and may reduce body temperature (Power *et al.*, 2018). Adjusting diets and feeding practices can help animals to cope with extreme temperatures (Cheng *et al.*, 2022).

Improved animal housing- In intensive livestock production systems, designing animal shelters to minimize heat stress is crucial (Gaughan *et al.*, 2019). Proper housing can provide a more comfortable micro-environment for animals and protect them from external climate extremes. To alleviate the negative effects of heat stress, housing with heat abatement technologies such as shade, fans, soaker, and mist sprayer are commonly used for lactating cows (Spiers *et al.*, 2018). Providing maximum shade in housing areas, holding pens, and tunnel ventilation are essential measures for heat stress (Toledo *et al.*, 2022).

Heat ameliorative measures- During periods of high temperatures, techniques like water cooling can be employed to lower the micro-environmental temperature within animal shelters (Godyñ *et al.*, 2020), while efficient air-cooling systems can be more expensive.

Community animal shelters- In arid zones and flood-prone areas, community shelters can provide a safe haven for animals during extreme weather events. These shelters offer protection against heat, heavy precipitation, and disease outbreaks (Aggarwal and Upadhyay, 2013).

Resource development, planning, and practices: These strategies aim to reduce vulnerability and exposure to climate-related risks. Key approaches include:

Weather forecasting and early warning systems- Providing farmers with weather forecasts and early warnings is essential for protecting livestock from extreme weather events such as heatwaves, cold spells, heavy rainfall, cyclones, floods, and disease outbreaks. Improved access to weather information is crucial for effective adaptation.

Coastal protection- Low-lying coastal areas are vulnerable to rising sea levels and cyclonic disturbances. Given the ongoing rise in sea levels and the anticipated increase in extreme weather events, well-planned coastal protection structures are vital to safeguard these areas.

Adaptation strategies are essential for reducing the current and future risks associated with climate change impacts on livestock production. These strategies encompass a wide range of actions, from natural adaptations in animal behavior and physiology to human interventions in nutrition, housing, cooling, and community-based solutions. Additionally, access to weather forecasting and early warning systems and the protection of vulnerable coastal areas are critical components of effective livestock adaptation to climate change. Implementing these strategies can enhance the resilience and sustainability of livestock farming in the face of a changing climate.

Mitigation of greenhouse gas emissions from livestock farming in the context of climate change

Mitigation efforts are crucial in addressing the greenhouse gas (GHG) emissions associated with livestock farming and their contribution to climate change. While the challenges of mitigation are significant, especially in countries like India with a large agricultural population and economic disparities, it is essential to pursue strategies that promote sustainable development and equity. India's contribution to GHG emissions from livestock, particularly enteric methane, is significant due to its large livestock population. However, per capita GHG emissions from livestock are lower than the world average.

Mitigation efforts in India should be balanced with the need for sustainable development and poverty eradication, considering the significant agricultural and rural population. Strategies should aim to improve the livelihoods of smallholder farmers while reducing emissions.

Equity and social inclusion must be integral components of climate policies. Mitigation measures should not disproportionately burden vulnerable communities or smallholder farmers.

Combining adaptation and mitigation efforts can lead to synergies that enhance resilience to climate change while reducing emissions. Livestock farming systems that are both climate-smart and economically viable should be promoted.

Mitigation pathways for reducing enteric methane emissions and improving animal resilience

Improvement in animal feeding: Implementing balanced feeding practices and effective feeding management can enhance nutrient utilization and reduce nitrogen and methane emissions. Ensuring that animals receive a well-balanced diet can improve their overall health and productivity while reducing the environmental impact. Dietary supplementation of low-quality feeds with energy or protein supplements could reduce CH_4 production as a result of improved efficiency of rumen fermentation. High levels of concentrate feed in diets increase propionate production, which decreases H_2 availability for CH_4 production (Patra, 2012).

Use of feed additives: Various feed additives, such as chemicals, essential oils, plant extracts, condensed tannins, probiotics, acetogens, propionate enhancers, alternate electron acceptors (nitrate and sulfate), bacteriocins, organic acids, halogenated methane analogue, and ionophore antibiotics, have shown promise in reducing methanogenesis in the rumen. These additives can help for the alteration of the microbial population in the rumen and decrease methane production (Patra, 2012).

New approaches: Research is ongoing to develop innovative approaches to reduce methane emissions, including vaccination of ruminants against methanogens and the use of plant-derived materials that divert hydrogen away from methane production without negatively affecting digestion and production. Promising materials like plant-derived liquid (PDL) and yeast-derived surfactant (YDS) have shown potential for reducing rumen methane production. Identification of rumen phages against methanogens that possess activity specifically against methanogens might be an area of exploration. Additionally, genetic selection of cows and buffaloes with higher feed efficiency and lower methane emission rates can be a sustainable long-term solution.

Heat ameliorative measures: Severe heat stress can lead to an increase in enteric methane emissions per unit of dry matter intake. Providing proper housing and heat ameliorative measures to protect animals from extreme heat stress can be effective in reducing methane emissions.

Supplementation of protected fat: Feeding protected fat to lactating cows and buffaloes, which bypasses rumen microbial degradation, can improve milk production and reduce enteric methane emissions.

Emission of methane and nitrous oxide in manure management: Proper disposal and management of farmyard manure, including its use for biogas production, can help reduce methane emissions. Biogas production not only provides clean energy but also mitigates methane release from manure. The slurry produced from biogas plants can be used as fish feed or for irrigation in agriculture, reducing the release of methane from manure while promoting sustainable practices.

Resilient animals: Selecting animals with inherent traits for resilience can be an effective long-term strategy (Carabaño *et al.*, 2019; Gaughan *et al.*, 2019). Traits such as long legs, short hair coat, high sweating rate, large surface area, efficient heat balance maintenance, low metabolic rate, high feed efficiency, tolerance to dehydration, and adaptable hormone and biochemical profiles can contribute to an animal's ability to cope with environmental stressors (Sejian *et al.*, 2017). Animals can build resilience through both their genetic potential and previous exposure to adverse conditions. This adaptability allows them to recover and perform better under stressful conditions (Banerjee *et al.*, 2014).

Overall, implementing these mitigation strategies and promoting resilient animals can contribute to reducing the environmental impact of livestock farming while ensuring the well-being and productivity of livestock in the face of climate change.

Conclusion

The impact of climate change on livestock production and animal health is a complex and multifaceted issue. Rising temperatures and changes in climate patterns are likely to have significant consequences for livestock farming. Increased temperatures and prolonged periods of thermal stress will lead to reduced livestock productivity, affecting milk, meat, wool, and draught power production. High temperatures can cause heat stress, which in turn affects animal growth, reproduction, and overall health. Climate change can alter the prevalence and distribution of diseases and pests that affect livestock. Incidences of diseases, particularly parasitic and protozoan infections, are likely to increase. These changes pose additional challenges to livestock health and management. Climate change can exacerbate resource scarcity, especially water shortages. Livestock are highly dependent on water for drinking, cooling, and other physiological functions. Water scarcity can have severe implications for livestock well-being and productivity. Climate change is expected to result in a substantial increase in the number of stressful days for livestock due to elevated temperatures and changing environmental conditions. This can lead to further challenges in managing and maintaining livestock health. The impact of climate change on livestock is influenced by the complex interaction between genetic factors and environmental conditions. Genotype-environment interactions play a crucial role in determining how animals respond to changing climate patterns. To address the challenges posed by climate change, strategies for adaptation and mitigation are essential. These strategies include improved animal management practices, feed additives, enhanced housing and shelter options, and the development of climate-resilient livestock breeds. India, in particular, is likely to face a significant water crisis, which will have severe consequences for livestock production. Ensuring access to water resources is crucial for sustaining livestock in the face of climate change. In conclusion, climate change is poised to influence various aspects of livestock production, health, and well-being. It is imperative for the livestock industry to implement adaptive measures and mitigation strategies to address these challenges and ensure the resilience and sustainability of livestock farming in the changing climate. Additionally, ongoing research and genetic selection for climate-resilient livestock breeds can play a vital role in securing the future of livestock production under shifting environmental conditions.

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