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Review

Climate Change and Livestock: Impacts on Productivity, Reproduction, and Adaptive Strategies

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ABSTRACT

Climate change poses significant challenges to livestock production and reproduction worldwide, affecting both the productivity and sustainability of the sector. The availability of feed, water, and grazing land are disrupted by rising temperatures, changed precipitation patterns, and an increase in the frequency of extreme weather events, leading to reduced animal growth, lower milk yields, and increased mortality. Heat stress, in particular, impairs reproductive performance, reducing fertility rates, increasing embryonic loss, and extending calving intervals. Furthermore, climate-induced shifts in disease patterns exacerbate health issues, reducing livestock resilience and productivity. In response, adaptation strategies such as improved animal housing, heat tolerance through genetic selection, and better resource management are essential to safeguard livestock systems. However, the interplay between climate change and livestock production underscores the need for sustainable practices that mitigate greenhouse gas emissions from the sector while ensuring food security and animal welfare.

Keywords: Animal health, Climate change, Livestock, Production, Reproduction

INTRODUCTION

The livestock sector is essential to ensuring food security andlivelihoods in developing countries. Agriculture and animal husbandry are farmers'primary sources of income, both of which have a direct impact on their financial circumstances. Climate change is one of the biggest risks to the long-term viability of livestock production systems in tropical nations (Sere et al., 2008; Sinha et al., 2017).Climate change is a multidisciplinary process that alters global or local weather patterns, posing a considerable risk to both humans and natural systems.Livestock production and productivity are under threat from a complex global challenge that affects both humans and the environment.Variations in the length, frequency, and severity of extreme weather events will be noticeable, and average surface temperature worldwide is expected to rise by approximately 3.7°C (with a likely range of 2.6°C–4.8°C) by 2100 (Howden et al., 2008; Stocker et al., 2013). These changes will directly and indirectly affect livestock production, reproduction, and health parameters. They will affect a complex range of Interacting biophysical factors that affect growth performance, reproductive performance, metabolic and health status, quality and yield of meat, milk and egg, and carcass quality (Henry et al., 2012; Nardone et al., 2010).

Climate, wind speed, precipitation, solar radiation, relative humidity (RH), and temperature are the main environmental factors that have an impact on livestock production systems (Hahn et al., 2003). Dairy animals'reproduction, health, and productivity are negatively impacted by heat stress (Sere et al., 2008). One of the main causes of the decrease in dairy cows'fertility is heat stress (De Rensis & Scaramuzzi, 2003; Dash et al., 2016). Climate change poses significant health challenges for livestock, including temperature-related illness, metabolic changes, and morbidity from extreme weather events (Nardone et al., 2010). Numerous studies show that climate change can negatively impact animal health and immune systems, potentially affecting disease distribution, growth, as well as reproductive health. (Thornton et al., 2009; Lacetera, 2012; Caminade et al., 2019; Ali et al., 2020; Bett et al., 2017).

Better housing and good management are two interventions to decrease the effects of climate change on livestock. These can mitigate the detrimental consequences of excessive heat on dairy animals'production and reproduction. Dairy farm profitability can also be increased by implementing different cooling systems, such as using sprinklers and foggers with or without fans, feeding management, diet modification, and altering reproductive protocols. The best method for increasing summertime milk production and reproduction in dairy animals is to install a cooling system (Sinha et al., 2017). Innovation and policy play a major role in addressing these challenges. Technological advancements, such as climate-resilient breeding, precision livestock farming, and sustainable feed production, offer practical solutions for enhancing adaptability and reducing environmental impact. Concurrently, robust policy frameworks can facilitate research funding, promote sustainable practices, and support capacity building among stakeholders. By integrating innovative technologies with evidence-based policies, it is possible to develop resilient livestock systems that mitigate climate risks, ensure food security, and promote sustainable development. Going beyond plans and promises is essential; it must be immediate and transformative. A clear roadmap to reach net-zero emissions must be outlined, along with increased ambition, coverage of entire economies, and a shift toward climate-resilient development. For future generations to have a sustainable future and to prevent disastrous outcomes, immediate action is required.

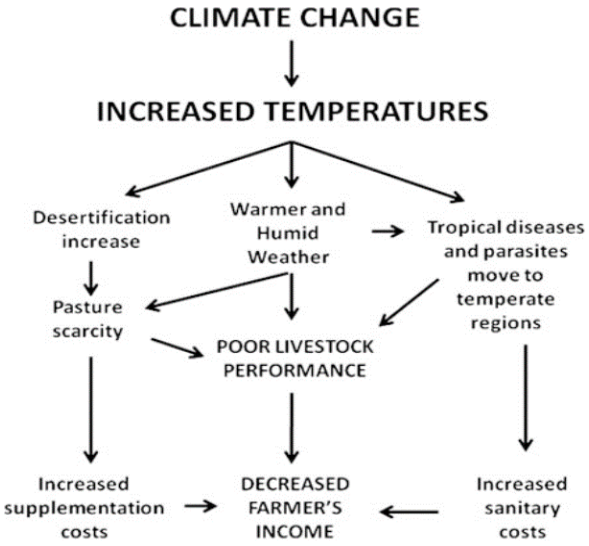

Figure 1. Schematic view of the expected outcome of climate change as a consequence of global warmiong on livestock (Lamy et al., 2012).

INFLUENCE OF CLIMATE CHANGE ON LIVESTOCK PRODUCTIVITY

Heat-related stress is among the main factors causing declines in dairy and beef production industries, and large financial losses have been associated with it (Nardone et al., 2010). The effects of climate changecan be both direct and indirect. Thedirecteffectsare on the physiology, productivity, and behaviorof animals such as rising temperatures and shifting rainfall patterns, which may result in the existing vector-borne diseases spreading more widely and macroparasites, and introducing and spreading new diseases (Henry et al., 2012),while indirect effects are on the availability of water, feed quality and quantity, and forage crops are some of the possible impacts of global warming on livestock (Craine et al., 2017). Rising temperatures and rising concentrations of carbon dioxide (CO^2) in the atmosphere and variations in precipitation volume, seasonality, and variability are some of the factors that are affected (Henry et al., 2012).

Other indirect effects are due to variations in feed resources linked to rangeland carrying capacity, ecosystem buffering abilities, accelerated desertification processes, increased water scarcity, and lower grain production. Expected feed shortages have additional unintended consequences due to the growing competition in the production of food, feed, and land use systems (Calvosa et al., 2009). The indirect consequences of global warming changes on

animal performanceare primarily due to changes in nutrition (Smit et al., 1996). Shade provided during late pregnancy improved neonatal lamb birth weight and survival (Kebede, 2016). This suggests that the uterine environment is impacted by heat stress, decreasing the total number of embryo cells and the size of the placentome, whichresults in smaller lambs. Additionally, in their early years of life, they would be more susceptible to dehydration. Temperatures between 15°C and 29°C do nothave an impact on growth performance. Elevated ambient temperature influences growth performance by reducing anabolic activity and elevating tissue catabolism. (Marai et al., 2007). The main cause of this decline in anabolism is a decrease in the voluntary feed intake of important nutrients. The increase in tissue catabolism is mostly seen in lean body mass and/or fat depots. Exposure to heat stress has a negative impact on lamb production, resulting in economic losses (Kebede, 2016).

The majority of the world's grazing areas and grasslands are found in the tropics and subtropics, and some of the world's poorest people rely on these lands for food security. In these regions, where socioeconomic factors like reliance on local food production and high susceptibility to land degradation increase the risk of food insecurity so that livestock is essential to fulfill nutritional needs. While historically, societies have adapted animal breeds to cope with high levels of climate fluctuation by adopting locally adapted breeds that are more resilient than many temperate phenotypes, future capacity to deal with hotter, drier, and more extreme conditions may require more adaptation expenditure(Henry et al., 2018).

Providing shade in the latter stages of pregnancy increased the birth weight and survival of newborn lambs. This implies that the uterine environment is affected by heat stress, which significantly lowers the number of embryo cells overall and the size of the placenta, resulting in smaller lambs. In their early years, they would also be more vulnerable to dehydration.High ambient temperatures have an impact on growth performance because they cause anabolic activity to decline and tissue catabolism to increase (Marai et al., 2007). A reduction in the voluntary intake of key nutrients from feed is the primary cause of this decline in anabolism. Tissue catabolism rises primarily in lean body mass and/or fat depots. Heat stress has a negative impact on lamb production, which results in financial loss.

EFFECTS ON LIVESTOCK MILK PRODUCTION

Animal behavior is highly influenced by climatic conditions and seasonal variations because of the

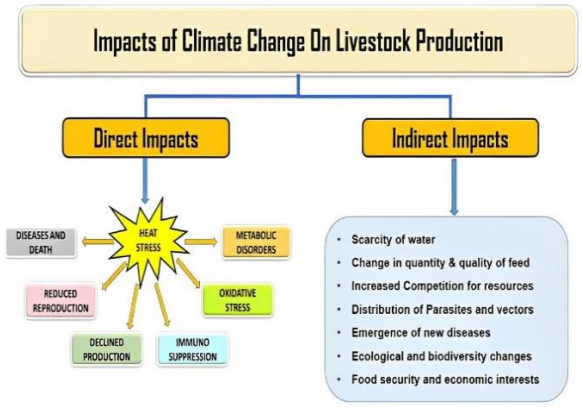

Figure 2. Impacts of climate change on livestock production (Mondal and Reddy, 2018).

neuroendocrine response to these factors, which in turn affects animal health and productivity (Baumgard and Rhoads, 2012; Sejian et al., 2010). The sustainability and viability of livestock production systems are severely threatened by climate change throughout the world (Gaughanet al., 2009). Climate factors have a greater impact on high production animals because of high air temperatures and relative humidity, especially for those raised in tropical climates (Gaughan et al., 2008).

In dairy animals, heat stress negatively affectsmilk production and composition, particularly in animals with superior genetic potential (Berman, 2005; Wheelock et al., 2010). It is thought that effective environmental heat loads that exceed 35°C cause lactating dairy cows'stress response systems to become active. In response, dairy cows consume less feed, which is closely associated with an energy imbalance and is the main cause of the decrease in milk synthesis (Wheelock et al. 2010). Reduced feed intake may account for up to 50% of the milk production drop in dairy animals; however, the remaining reasons may be metabolic responses to heat stress since heat stress response modifies post-absorptive protein, lipid, and carbohydrate metabolism (Baumgard and Rhoads, 2013). Heat-stressed cows and ewes showed elevated basal insulin levels and improved insulin response, which accounts for the change in glucose utilization in non-mammary gland tissue that influences milk synthesis (Wheelock et al., 2010; Rhoads et al., 2013; Kebede., 2016). Hot and humid environments impact milk yield and quality. The percentages of milk protein, solids-not-fat (SNF), and fat dropped by 16.9%, 18.9%, and 39.7%, respectively (Kadzere et al., 2002). Climate change can lead to more frequent heat waves and other extreme weather conditions, which can cause heat stress in livestock. Heat stress can cause the animal to reduce feed intake and it also may impair

the mammary gland's ability to produce milk.It may also cause to reduce the availability of feed, so it may also cause to reduce the production of milk.

EFFECTS ON LIVESTOCK HEALTH

Many climate change-related health issues affecting livestock, such as the spread, distribution, and emergence of livestock diseases, have a major impact on livestock (Nardone et al., 2010). Seasonal and longer-term climatic variations significantly impact the distribution and effects of animal vector-borne diseases, including bluetongue, Rift Valley fever, and African horse sickness (Thornton and Gerber, 2010). instance, mild winters in the affected areas of europe in 2006–2007 and 2007–2008 likely enhanced the habitat of some Culicoides species that may serve as vectors for bluetongue disease in these areas, thereby facilitating their geographic spread. According to certain research, the main bluetongue vector in southern Europe, C. imicola, has expanded geographically, reaching previously unobserved regions like the north of Spain (Goldarazena et al., 2008). Many factors, including vectors, are linked to the complexity of climate change (McDermott et al., 2002). Though the effects vary among the main species groups, Tsetse are extremely sensitive to environmental change, whether it be from the climate or direct human impacts on their habitat. Although riverine species are more able to adapt to growing human population densities than the other groups, forest and riverine species are far more susceptible to climatic factors than savannah species (Patz et al., 2005). Livestock infectious diseases may be impacted by climate change in a number of ways (Baylis and Githeko, 2006). Effects on hosts include changes in disease distribution that may impact vulnerable animal populations; effects on vectors include patterns of precipitation and temperature fluctuations that may impact the abundance and distribution of disease vectors; and effects on epidemiology include modified transmission rates between hosts. Higher temperatures can also have an impact on pathogens and parasites (Randolph, 2008).All health-related issues of livestock are directly or indirectly responsible for the decrease in the productivity of livestock animals.Pathogens like anthrax, dermatophiloses, and black quarter that continue to live outside of their final host body are significantly impacted by temperature and humidity. Bacillus anthracis spores are the source of the fatal zoonotic disease anthrax. In pasture land, this spore may remain viable for ten to twenty years. The successful germination of anthrax spores is influenced by temperature as well as other meteorological factors like humidity, rainfall, pH, soil water activity, and nutrient availability. Drought, soil erosion, and heavy rains can activate dormant spores and increase an animal's exposure (WHO, 2008).

EFFECT OF CLIMATE CHANGE ON ANIMAL REPRODUCTION

Elevated temperatures and humidity levels in the air can directly alter and impair different reproductive system tissues and organs in animals of both sexes. Climate change has a negative impact on both male and female livestock reproductive functions (Amundson et al., 2006; Sprott et al., 2001). Climate change will affect reproductive rhythms via the hypothalamic-hypophyseal-ovarian axis as temperatures rise and radiant heat load intensifies. Gonadotrpin releasing hormone (GnRH) from the hypothalamus and gonadotropins such as Follicle stimulating hormone (FSH) and Leutinizing hormone(LH) from the anterior pituitary gland are the primary factors that regulate ovarian activity (Madan and Prakash, 2007). Throughout the summer, crossbred cattle and buffaloes show low rates of conception and estrus expression. Poor estrus expression in buffaloes during the summer period may be attributed to low estradiol levels on the estrus day (Upadhyayet al., 2009).

Climate change has a major effect on the reproductive processes of cattle and buffalo (Dash et al., 2015). Extreme heat and high relative humidity levels during the summer have a negative effect on cattle reproduction. The reproductive characteristics of buffaloes and cattle are negatively impacted by heat stress. Dairy cows'conception rates decreasewith increased heat and humidity in cattle and buffalo (Morton et al., 2007; Dash, 2013; Schuller et al., 2014).

Reproductive performance is impacted by heat stress through altered blood flow and hormone production, resulting in 20%-30% decrease in oestrus and conception rates in ruminant animals in the summer (King et al., 2006). Additionally, it affects the development of the oocyst and embryo (Stewart et al., 2011), the estrus cycle (Wolfenson et al., 2000), and the quality of the semen (Nichi et al., 2006).

The anterior pituitary gland releases Adrenocorticotropin hormone (ACTH) in response to heat stress, which prompts the adrenal cortex to release glucocorticoids and cortisol. Additionally, luteinizing hormone release is inhibited by glucocorticoids. Thermal stress-induced hyperprolactinemiaprevents both FSH and LH from being secreted at the hypophyseal level (Singh et al., 2013).

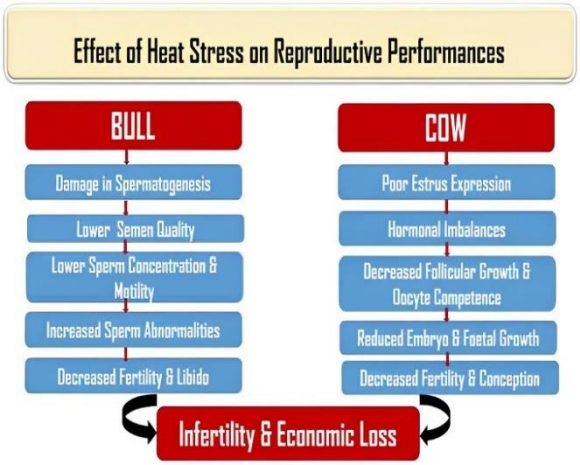

Figure 3. Effect of heat stress on reproductive performances of male and female animals. Source (Mondal and Reddy, 2018).

ALTERATION IN THE FEMALE REPRODUCTIVE MECHANISM CAUSED BY HEAT STRESS

Cattles observed an increase in early embryonic development during warm seasons for a number of reasons. At different phases of female reproduction, heat stress creates a variety of unfavorable conditions. Heat stress has a direct impact on oocyte competence and follicular development (Abdelatty et al., 2018). Additionally, heat stress decreases weight and the corpus luteum'sdiameter, the amount of progesterone released, and the consistency of the oocytes, all of which contribute to pregnancy loss. HS alters the endometrial environment by increasing glycoprotein 2 and neurotensin levels, which can cause Fertility problems in the summer (Fernandez-Novo et al., 2010).

All of these factors reduce the rate of fertilization and the quality of any resulting embryos, increasing the likelihood of pregnancy failure and decreasing reproductive success. Beef and dairy cattle, on the other hand, have demonstrated this behavior. As the intensity of the heat stressincreases, the rate of conception in lactating cattle drops. Additionally, from one month prior to breeding until two weeks following breeding, the heat stress event may have an impact on conception rates (Lees et al., 2019; Fernandez-Novo et al., 2010).

Furthermore, heat stress is associated with a smaller conceptual scale that may impact the recognition of maternal pregnancy and the function of the corpus luteum. Moreover, heat stress has been connected to a pre-implantation pregnancy that is compromised, with a higher chance of foetal loss from days 21 to 30 of pregnancy (Fernandez-Novo et al., 2010). The reduction of blood flow to the uterus can also affect the supplementation of nutrients to the embryo and decrease the uterine secretion of hormones, which can further make things difficult.Heat stress is the main factor that affects dairy cow lactation. There is a much lower chance of infertility in beef cattle and non-lactating dairy animals during heat stress (Hansen, 2019).

HS also reduces the duration and potency of oestrus because heat stress decreased follicular estradiol and oestrus levels may have decreased as well. Reduced oestrus speech could also be caused by the physical inactivity brought on by heat stress. Cows become less active during oestrus, which makes them less likely to mount other cows. Long-term exposure to high temperatures reduces oestrus signs and lessens the severity of pregnancy, which lowers the rate of pregnancy. In addition, hot weather during the summer induces ovulation without any oestrus symptoms (Khan et al., 2020).

ALTERATION IN THE MALE REPRODUCTIVE MECHANISM CAUSED BY HEAT STRESS

Bulls make up a small portion of the herd, and their reproduction is directly related to oocyte fertilization. Mammal species have a special physiological mechanism called thermoregulation that helps to protect reproductive processes from changing climate (Gokhale & Sharma., 2019).

Bulls require a testicular temperature of 33-34°C for spermatogenesis (Takahashi, 2012). The bovine spermatogenesis process is complex and takes 61 days to complete (Rahman et al., 2018). It is challenging to identify the stage of spermatogenesis at which heat stress affects spermatozoa. Heat stress interrupts the spermatogenesis cycle, as evidenced by the collection of ejaculate during the spermatogenesis phase. The stages of spermatogenesis most vulnerable to heat stress are primarily the early stages of spermatogenesis (Domenech and Fricke, 2023). Cell vulnerability at particular times is caused by inefficient protamine replacement of histones, which causes sperm chromatin conformation shifts (Rahman et al., 2018).

Testicular function is adversely affected by hyperthermia. Heat stress has a negative effect on reproductive tissue, as evidenced by symptoms like low sperm count, poor morphology, and lack of germ cells. The Deoxyribonucleic acid (DNA) in the sperm nucleus is arranged in accordance with the needs of each individual cell. In spermatozoa, a particular type of nuclear protein that condenses chromatin 6 to 20 times more than nucleosome-bound DNA and the nucleus. Heat stress during spermatogenesis causes chromatin conformation changes in sperm, which

further unbalances DNA methylation conformation and contributes to zygote reorganization. (Gokhale& Sharma., 2019; Rahman et al., 2018).

The high compaction is caused by the substitution of histone-bounded chromatin with protamine-bounded chromatin, which is required for the secure liberation of oocyte sperm DNA in the female reproductive tract during oxidative stress depletion. Furthermore, the sperm nucleus is extremely condensed, which inhibits sperm DNA transcription. The DNA damage results from sperm nucleus hypo-proteinemia., and it causes male subfertility or infertility (Raman et al., 2018).

HS causes a decrease in glutathione peroxidase (Gaps) and other antioxidant-related enzymes in the seminal plasma of cows while increasing the levels of oxidative marker and thiobarbituric acid reactive substances (TBARs) (Takahashi, 2012). HS lowers plasma levels of luteinizing hormone (LH) in bulls. HS has a major negative impact on male reproductive efficiency.

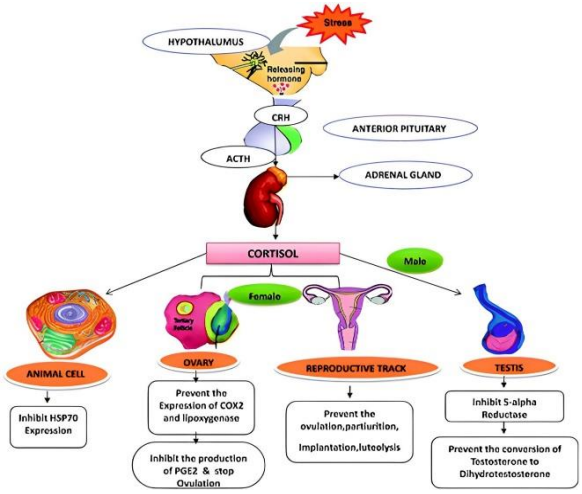

Figure 4. There are various ways that stress impacts livestock reproduction. The anterior pituitary releases ACTH in response to CRH, which is produced by a stress stimulus on the hypothalamus. The adrenal cortex releases cortisol in response to ACTH. The main glucocorticoid that suppresses reproductive function is cortisol, which acts on animal cells, the ovary, the female reproductive tract, and the male testis. Source (Naqvi et al., 2012).

ADAPTATIVE STRATEGIES FOR LIVESTOCK TO COPE WITH CLIMATE CHANGE

Adaptation strategies can help livestock and crop productivity withstand climate change (USDA, 2013). Adaptation strategies include modifications in the management system, improvement in feeding practices, breeding strategies, institutional and policy changes, and changing perceptions of farmers and adaptive capacity (Rowlinson et al., 2008). Heat stress can be reduced through a multidisciplinary approach. It should include modifications to the microenvironment, genetic improvement, and nutritional management, which are critical components for long-term livestock production in hot environments. The following strategies are important regarding adaptation to cope with changing climate.

MODIFICATION OF MICRO ENVIRONMENT

One of the most crucial steps to take in a hot environment is to modify the microenvironment to enhance the heat dissipation mechanism and reduce heat stress. The most popular strategy for reducing heat stress is to alter the area around the cow way by adding shade and using an evaporative cooling system with or without fan (Atrian and Shahryar, 2012). Enhance cows 'ability to reproduce by employing efficient cooling systems that mix evaporative cooling with cross or tunnel ventilation (Kadokawa et al., 2012). Modifying production and management systems can include diversifying livestock and crops, integrating livestock with forestry and crop production, and shifting farm operations timing and locations (IFAD, 2010).

BREEDING STRATEGIES (GENETIC MODIFICATION)

There is a need to find animals in high-yielding breeds that can tolerate the heat and use genetic selection to increase cooling capacity and genetic variation (Kimothi and Ghosh, 2005).Breeding strategies that are modified can help animals become more resilient to diseases and heat stress, as well as enhance their growth and reproduction (Henry et al., 2012. In comparison to darker colors and longer hair coats, cattle with lighter, thinner skin, shorter hair, and a larger diameter of hair coat color are better suited to hot climates (Bernabucci et al., 2010). Therefore, maintaining the valuable adaptations provided by breeding strategies while increasing livestock production presents a challenge that will necessitate further research (Thornton et al., 2008). However, their implementation faces several challenges. Technological hurdles include the complexity of multigenic traits, risks of unintended genetic effects, and the trade-off between adaptation and productivity. Ethical concerns about animal welfare and public acceptance, coupled with cultural resistance, further complicate adoption. Environmental risks, such as ecosystem disruption and reduced genetic diversity, and economic barriers, including high costs and limited accessibility for smallholder farmers, also pose significant obstacles.

IMPROVING FEEDING MANAGEMENT PRACTICES

Enhancing feeding practices as a means of adapting can indirectly raise livestock productivity efficiency (Havlík et al., 2013). A few suggested feeding strategies include adjusting the diet's composition as well as the timing and frequency of feedings (Renaudeau et al., 2012). These practices can reduce climate change by increasing feed intake, reducing heat load, decreasing feed insecurity during dry seasons, and lowering animal malnutrition and mortality rates. (Thornton and Herrero, 2010; (Renaudeau et al., 2012; IFAD, 2010). Field-based livestock adaptations include changing pasture rotation, adjusting grazing and reproduction timing, changing forage and animal species, reevaluating fertilizer applications, altering integration within mixed livestock/crop systems by using adapted forage crops, making sure there are enough water supplies, and using nutritional supplementary feeds and concentrates (Rötter and Van, 1999).

LIVESTOCK MOBILITY STRATEGIES

Shifting the locations of livestock and the production of crops can decrease soil erosion and enhance the retention of moisture and nutrients. (Kurukulasuriya and Rosenthal, 2003). Mobility remains the most important pastoralist response to spatial and temporal variations in precipitation. Encouragement of mobility is a strategic response to the variability and scarcity of pastures. The adaptation of these livestock systems to climate change can be greatly improved by strengthening livestock mobility, a traditional tactic used by transhumance and nomadic herders to balance the demands of animal production with shifting range land resources (FAO, 2021). During the period of ruminant livestock mobility, the nomads developed a system of natural resource management based on shared responsibility, consensus, and pastoral solidarity in order to adapt their production to the challenging eco-climatic conditions (Tibbo, 2012). The effects of climate change are more likely to affect pastoral communities as they become less mobile. Ruminant livestock production, which includes ruminant animal movements, feed basket adjustments, health interventions, and animal off-take for the market, can buffer shocks caused by climate-driven variability in livestock production (FAO, 2016). Climate change, however, may force livestock to walk great distances in search of feed and adapt to less frequent watering (Tibbo, 2012).

CAPACITY BUILDING FOR RUMINANT LIVESTOCK PRODUCERS

Raising the awareness of livestock producers and herders of global changes is necessary in order to help better understand and adapt to climate change. Resilience is the ability of ruminant animals to reduce the impact of disturbances or to recover to their resting state as soon as possible (Oliver et al., 2012). Ruminant livestock production requires cost-effective and efficient adaptation techniques to boost productivity (Jones et al., 2013). These could be: (i) providing shade and water to lessen heat stress from rising temperatures; (ii) reducing the number of livestock; fewer but more productive animals produce more efficiently and emit fewer greenhouse gases from livestock production (IFAD, 2016); (iii) altering the composition of the livestock/herd (selecting large animals rather than small).

Despite advancements in understanding its impacts, critical research gaps persist in developing effective adaptation strategies. Region-specific measures tailored to local climatic and socio-economic conditions remain underexplored, while the genetic basis of resilience traits in livestock requires further investigation to breed climate-adapted animals. Insufficient attention has been given to alternative feed resources, disease dynamics under changing climates, and sustainable water management practices.

ECONOMIC IMPLICATIONS OF CLIMATE CHANGE ON LIVESTOCK

Globally, livestock production supports the livelihoods of approximately 900 million poor people and employs 1.3 billion people Climate change lowers livestock productivity due to direct effects, changes in the prevalence and spread of diseases, heat stress and associated welfare problems and indirect effects on feed crop availability and forage quality (Escarcha et al., 2018).Domestic animals are used by human populations all over the world for a variety of purposes, primarily the production of meat, fat, milk, and other dairy products, eggs, and fibers like cashmere or wool, as well as for other uses like transportation, drafting, and fertilizer provision, particularly in developing nations. There are negative consequences of extreme weather conditions on livestock production (Kebede, 2016). All these disruption impose highly economic impacts on the people of developing countries.

CONCLUSION

Climate change significantly impacts livestock production and reproduction through rising temperatures, altered precipitation patterns, and increased frequency of extreme weather events. These challenges lead to heat stress, reduced feed

availability, lower reproductive efficiency, and increased disease susceptibility among animals, thereby threatening livestock productivity and food security.

However, adaptive strategies are crucial to mitigate these effects. Approaches such as genetic selection for heat-tolerant breeds, improving feed quality and water management, enhancing housing systems to reduce heat stress, and incorporating sustainable practices like rotational grazing and precision livestock farming can help reduce the negative impacts of climate change. Future research in this field must focus on key areas include improving heat tolerance through genetic selection and biotechnology, exploring climate-resilient breeds, and enhancing understanding of epigenetic mechanisms that mediate animal responses to stress. Investigating nutritional interventions, such as heat-stress-mitigating diets and precision feeding strategies, is important for maintaining productivity under extreme conditions. Research into housing and management systems, including sustainable cooling technologies and optimized shelter designs, will provide essential tools for mitigating heat and cold stress. These measures, coupled with policy support and research innovations, are essential to sustain livestock production in the face of ongoing climatic challenges. The sector can maintain resilience through adaptive management and contribute to the global demand for animal-derived products while minimizing environmental impacts.

AUTHOR'S CONTRIBUTIONS

Sajad Ali Laghari, Abdul Saboor, Fayaz Hussain, Taj Muhammad, Iqrar Uddin and Abdul Razzaque conceptualized the study and searched the literature. Sajad Ali Laghari wrote and designed the manuscript. Qudratullah Kalwar and Muhammad Mohsen Rahimoon reviewed and edited the manuscript.

CONFLICT OF INTEREST

There is no conflict of interest for this manuscript.

GLOSSARY

Epigenetic mechanisms: These are biological processes that regulate gene expression without changing the DNA sequence.

Precipitation patterns: Precipitation patterns are the distribution, intensity, and timing of rainfall and snowfall.

Genetic modification: Genetic modification is the process of altering the DNA of an organism to change its characteristics.

Phenotypes: Phenotypes are the observable traits or characteristics of an organism, such as its appearance, behavior, or biological functions.

Gonadotropins: Gonadotropins are hormones that stimulate the activity of the gonads (ovaries in females and testes in males). They regulate the processes like the production of eggs, sperm, and reproductive hormones.

Hyper-prolactinemia: Hyper-prolactinemia is a condition where there is an abnormally high level of prolactin, a hormone produced by the pituitary gland.

Neurotensin: Neurotensin is a small protein-like molecule (peptide) that acts as both a hormone and a neurotransmitter, found in brain and digestive system and regulate functions like pain perception, body temperature, appetite, and digestion.

Glutathione peroxidase (GPx): Glutathione peroxidase (GPx) is an enzyme that helps protect cells from damage caused by harmful molecules called free radicals.

Thiobarbituric acid reactive substances (TBARs): Thiobarbituric Acid Reactive Substances (TBARs) are byproducts formed when fats in the body or food are damaged by oxidation.

Microenvironment: A microenvironment is the small, specific environment surrounding a cell, tissue, or organism that directly affects its behavior and function.

Multigenic traits: Multigenic traits are characteristics that are influenced by multiple genes working together, rather than a single gene.

Macroparasites: Macroparasites are larger parasites, such as worms (e.g., roundworms, tapeworms) and arthropods (e.g., ticks, lice), that live in or on a host.

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