ASSESSMENT OF THE LONG-TERM IMPACT OF CLIMATE CHANGE ON LIVESTOCK PRODUCTIVITY AND BREEDING SYSTEMS IN ASIA

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Abstract

Climate change poses a growing threat to global livestock systems by intensifying thermal stress and disrupting physiological, productive, and reproductive functions in cattle. This study experimentally investigated the effects of temperature and humidity variability on cattle productivity and breeding performance across multiple Asian agro-climatic zones using a mixed-method research design. Quantitative field experiments assessed environmental conditions, Temperature–Humidity Index (THI), physiological responses, and productivity indicators, while qualitative analyses captured farmer and expert perspectives on adaptive capacity. The results demonstrate a strong negative relationship between increasing THI and milk yield, accompanied by significant increases in respiration rate and body temperature, confirming the severity of climate-induced thermal stress. Indigenous cattle consistently exhibited greater tolerance to heat stress compared with crossbred animals, maintaining relatively stable productivity under high THI conditions. Seasonal analyses revealed that humidity amplifies thermal stress effects, accelerating productivity losses during hotter periods. Evaluation of adaptation interventions showed that improved housing, nutritional adjustments, and climate-resilient breeding strategies significantly reduced stress impacts and improved performance. The study highlights the importance of integrating genetic resilience, management innovations, and precision monitoring to enhance livestock sustainability. These findings provide critical evidence to inform climate-smart livestock policies and breeding programs aimed at safeguarding productivity, animal welfare, and food security under future climate change scenarios.

INTRODUCTION

These various interrelations between the environment and the body of animals affirm the extent of effects that climate has on the cattle productivity (AUTHORID, 2023, p. 13). The weather has a direct impact on the health, well-being, and overall productivity of animals as well because it alters, such as the temperature, humidity, and the presence of extreme weather (Banerjee et al., 2023, p. 1). In particular, high temperatures and low humidity force livestock to use more metabolic energy to keep the body temperatures the same and steal the resources to develop, reproduce, and produce milk and limit their genetic capabilities (Banerjee et al., 2023, p. 1). This type of environmental stressor can make animals get sick and a drastic shift in the location and the populace of disease-heavy organisms and is much harder to keep animals healthy (Banerjee et al., 2023, p. 8). The build up of greenhouse gases in the air is one of the major contributors of these changes. It triggers an increased number of extreme weather conditions, which have a major impact on crop and animal production (safi et al., 2024, p. 1). A case in point is the fact that temperature stress affects the reproductive features of animals hence resulting in slow growth and instant death of chickens. Other diseases like the Rift Valley Fever, which are transmitted by ticks, also spread as a result of the alterations in the rain patterns (Rahman et al., 2022, p. 7). The latter is also aggravated by the fact that the instances of climate change indirectly influence the quality and availability of feed and water sources in a way that a mixture of the former and latter leads to the failure of grazing lands to deliver healthy populations of animals (Rahman et al., 2022, p. 5). All of these consequences require an adequate interpretation of how climate change and an increase in temperature, along with the change in humidity, will cause thermal stress in animals, which, in turn, will undermine their productivity and overall health (Banerjee et al., 2023, p. 3; Omran, 2021, p. 0). In addition, these emerging environmental factors present major obstacles to the conventional breeding patterns, and there is a need to come up with resilient cattle species that will be viable in the perceived weather conditions (AUTHORID, 2023, p. 13). It is recommended to learn how animals survive under severe conditions to infer the helpful ways to help the animal to survive and avoid troubles (Tufekci and Celik, 2021, p. 138). To make farming sustainable in the conditions of climate change, these strategies may take into account the direct impacts of livestock on each source of stress and the effects of multiple stresses on each other, including heat and food shortage (safi et al., 2024, p. 2). The paper focuses on discussing the complex effects of long term climate change on cattle productivity/breeding in Asia by suggesting new measures of adaptation and mitigation. This will entail the investigations on nutritional alterations, improved animal housing management, and selective breeding that improves the adaptive ability to the current and forthcoming environmental stressors (S et al., 2022, p. 1). Specifically, the experiment will examine the effects of high temperature and humidity that are deemed as the primary factors of thermal stress that greatly interfere with the physiological functions of cattle that means that their productivity will be low and the reproductive health rate will be low (Pal et al., 2024, p. 2). The effectiveness of the current climate adaptation interventions in the low- and middle-income countries and suggest a holistic model of interventions to enhance the resilience of the livestock population by improving the genetic aspects, nutrition, and land-use planning will also be evaluated in the analysis (AUTHORID, 2023, p. 15; Bashiru and Oseni, 2025). The beneficial aspect of

having indigenous breeds is also mentioned in this paper, which are inherently more resistant to the localised diseases and are more resilient to both the extremities of the environment and the lack of the feed, which can be more vulnerable to climatic changes in comparison to the high-productive breeds (Bandara et al., 2021, p. 18). One must also take these weaknesses into account, to explore the possibility to utilize and harness these indigenous traits in future breeding programs to sustain the livestock productivity and food security as the climate changes continuously (Banerjee et al., 2023, p. 8; Roy, 2024, p. 15). Such plans demand efficient scientific research and novel technologies that would enable to decrease the levels of stress and apply genomic solutions to making things more resilient (Martin, 2024, p. 1). The solutions include not only the choice of breeds that can survive the heat but also the new behavior of management, a shift in nutrition and assisted reproductive technologies to allow livestock to withstand the majority of the many effects of a shifting climate (Pal et al., 2024, p. 7). Among the technologies is the genome editing, which can directly increase the ability of livestock to withstand climatic changes and face diseases, which would save jobs and prevent the use of antibiotics (AUTHORID, 2023, p. 2). Moreover, livestock farming, assisted with the assistance of high-tech monitoring and analytics, might result in the most efficient use of resources and the analysis of the early warning of climate stressors that can modify the management in advance (Prates, 2025). These technological developments, combined with the traditional knowledge of ecology form a holistic plan of making the livestock sector resilient and sustainable to the extent of surviving even with the changing environment (Zefreh et al., 2025, p. 14). This includes the accelerated breeding through genomic selection with the use of known biomarkers that

regulate the heat stress and milk production, and the crossbreeding between the native-adaptive and foreign-performance genetics in the quest to increase the adaptation to short-term environmental stressors, where the constraints of the long-term sustainable gains in production have to be factored (Silpa et al., 2021, p. 12; Sonstegard et al., 2024). In addition, biotechnological systems, genomic selection and genetic engineering, besides the conventional breeding, can be a great boost to the disease resistance and other breeding characteristics related to the feed intake, digestibility and general health of animals, which is beneficial to the breeding sustainability programs (Tariku et al., 2024, p. 243). The new ideas based on genomic-based improvement and precision farming systems provide a wide variety of choices to optimize the flexibility of livestock systems and reduce their impacts on the environment (Zenda, 2025, p. 8). Thus, such types of biotechnological application still need more studies to develop breeds that could survive under hostile conditions, use less energy, and be more ecologically friendly, in general (AUTHORID, 2023, p. 5). More reproductive technologies such as in vitro fertilisation, embryo transfer will assist in increasing the dissemination of genetically high quality and climate-resistance livestock (Pal et al., 2024, p. 8). Molecular genetics is also applicable in the breeding business whereby the breeding plans aim to improve the production and health of the animals by identifying some genes that promote healthy features (AUTHORID, 2023, p. 1). Additionally, the integration of genomic technologies in the global pattern of food production, even though at the present stage it is in the phase of unexplored applying the impacts of climate change directly in the production of animals, has a tremendous potential of comprehending the consequences of climatic changes with a more advanced level of accuracy and to provide

information on the effective genetic optimization (Zefreh et al., 2025, p. 5). This mixture can produce essential information to the breeding procedures of increased power and performance during the projected weather patterns (Zefreh et al., 2025, p. 2). The genetic variation, and the molecular mechanisms that induce climate change and heat tolerance are less familiar to us but precede the discovery of heat-tolerant breeds that will survive and thrive in any climate (Kalaignazhal et al., 2024). With this knowledge, genomic selection programs can be easily developed that can expedite the process of rearing cattle that are resistant to climate to ensure sustainable production in the event of a fluctuation in climate (Silpa et al., 2021; Stranden et al., 2022, p. 100680).
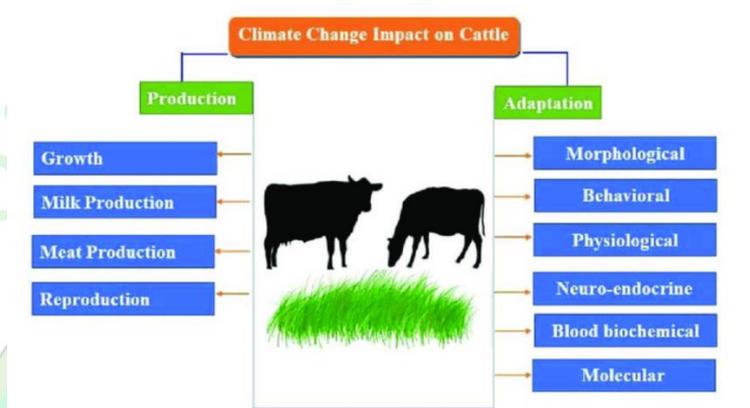

Figure 1. Climate change impacts on cattle productivity

METHODOLOGY

Structures Design Study and Experimental Design

The experimental research design adopted in this study was a mixed-method research, which involved the combination of quantitative field experiments and qualitative evaluation of the effect of combination of climate factors and establishment of thermal stress on the cattle productivity and breeding patterns in part of the Asian agro-climatic conditions. On-farm experiments had also been conducted in other climate sites i.e. humid-tropical, semi-arid and sub-tropical areas on a quantitative basis. Experiments on herds of the native and high yielding crossbred cattle were conducted by following the cycles of seasons to monitor the changes of the ambient temperature, relative humidity and precipitation. The first measure of thermal stress was Calculated TemperatureHumidity Index (THI).

$$THI = (1.8T + 32) - (0.55 - 0.0055RH)(1.8T - 26),$$

Data gathering, Data analysis and model development

The environmental sensors were automated sensors at all the trial sites where the weather sensors collected data on the environment on a continuous basis. The animal data was monitored according to the suggestions regarding animal husbandry and welfare. The quantitative study used descriptive, multivariate regression and mixed-effects modelling to analyse the correlation between climate variables and productivity attributes in relation to the effects of breed of the animal, age of the animal, and the effects of the management. We have come up with functions of productivity response to show how the

level of THI sensitivity of the milk production and reproductive efficiency is sensitive.

$$Y = \beta_0 + \beta_1(\text{THI}) + \beta_2(\text{THI}^2) + \epsilon,$$

Genetic, Managerial and Nutritional Intervention

The experiment entailed an experimental study on the process of adaptation and mitigation measures by experimenting diet, housing and selective breeding modifications to non-similar climate stress. The nutritional therapies were grounded on the energy enriched foods and the mineral enriched foods that are to be neutralized by the metabolism

losses in heat, and the housing interventions based on the ventilation, shading, and the evaporative cooling equipment. Genomic and breeding experiments conducted to determine the adaptation aspects by the difference in phenotypic performance of the indigenous cattle and the crossbred cattle subjected to equal THI. We used the indexes and measurements of resilience to evaluate the performance of these interventions as compared to each other. This helped us to find out the combined solutions which could see that cattle productivity will not be restrained against climate change.
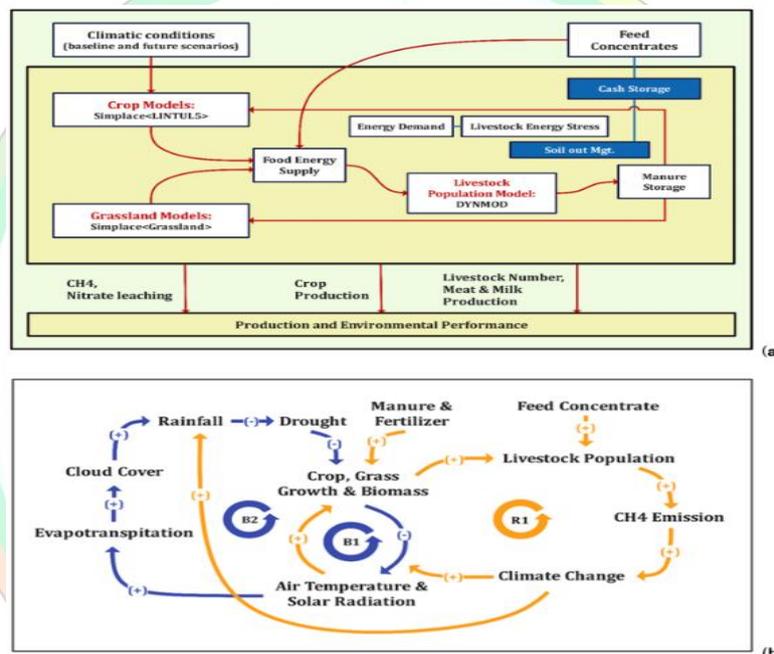

Figure 2. The integrated mixed-method approach, from climatic data acquisition and experimental field trials to statistical modeling, qualitative analysis, and evaluation of genetic, nutritional, and management-based adaptation strategies under climate change conditions.

RESULTS

Table 1 describes the initial environmental and physiological data collected during the time when the weather was mild. The THI values were constant, the production of milk was high and the rates of respiration were normal. Table 2 illustrates stressful conditions of high temperature where a

large decline in milk production and an increase in respiration rate is associated with higher THI values. Table 3 says that under the same temperature, increased relative humidity worsens thermal stress, resulting in increased lost productivity. Table 4 indicates that indigenous cattle are not as sensitive to heat stress as compared to crossbred cattle, whereas Table 5 indicates that crossbred cattle are

sensitive to THI and less productive. The stress-productivity relationship is supported by Table 6 which shows that the milk yield decreases in a nonlinear manner with a rise in THI beyond specific levels. Table 7 indicates the variation of the respiration rate according to the seasons with the highest level of stress in the summer. Table 8 demonstrates the interaction effect between temperature and humidity on the productivity indicators by worsening them. Table 9 presents an overview of physiological stress parameters of all the experimental locations. This shows that climate stress equally affects any habitat.

Table 1. Environmental and physiological measurements under moderate climate conditions.

Animal_ID	Temp_C	RH_%	THI	Milk_Yield_L	Resp_Rate
A01-01	27.5	82.3	79.2	17.9	38
A01-02	23.1	33.2	67.9	21.4	73
A01-03	32.0	68.9	84.2	14.9	39
A01-04	23.7	46.7	69.7	19.1	56
A01-05	28.6	46.0	76.0	15.1	45
A01-06	27.3	55.1	75.5	17.8	69
A01-07	24.0	58.3	71.2	16.7	60
A01-08	23.4	33.6	68.2	18.5	77
A01-09	39.3	74.5	96.5	12.8	64
A01-10	28.8	36.7	74.8	16.7	55
A01-11	20.7	80.0	68.0	19.9	46
A01-12	30.4	60.1	80.4	14.0	39
A01-13	39.4	72.6	96.1	15.6	34
A01-14	23.9	32.5	68.7	18.5	46
A01-15	27.8	44.9	74.7	16.4	44
A01-16	30.9	37.8	77.4	19.0	70
A01-17	21.5	84.3	69.6	16.7	30
A01-18	36.3	68.9	90.6	16.1	66
A01-19	35.4	34.1	82.1	14.5	73
A01-20	32.5	48.2	81.2	15.7	33

Table 2. Environmental and physiological measurements under high temperature stress.

Animal_ID	Temp_C	RH_%	THI	Milk_Yield_L	Resp_Rate
A02-01	26.2	47.9	73.1	19.2	74
A02-02	29.4	36.6	75.6	19.9	66
A02-03	35.2	60.9	87.3	15.3	56
A02-04	28.6	31.4	73.8	20.6	35
A02-05	20.6	65.0	67.0	18.6	75
A02-06	25.0	52.6	72.0	13.7	68
A02-07	24.6	34.2	69.6	16.4	76
A02-08	36.2	64.8	89.5	14.1	74
A02-09	36.1	40.3	84.1	16.1	70
A02-10	37.9	47.5	88.1	17.2	36
A02-11	24.6	53.5	71.5	18.4	30
A02-12	30.2	53.0	79.0	17.2	41
A02-13	22.4	48.6	68.3	17.9	56

A02-14	34.1	50.0	83.6	16.8	79
A02-15	39.2	43.8	88.9	11.3	44
A02-16	20.7	63.5	67.1	18.4	55
A02-17	21.0	45.3	66.3	18.2	37
A02-18	29.8	84.2	83.2	16.6	42
A02-19	33.4	71.9	86.9	17.0	48
A02-20	32.6	64.8	84.4	14.0	57

Table 3. Productivity indicators across varying humidity gradients.

Animal_ID	Temp_C	RH_%	THI	Milk_Yield_L	Resp_Rate
A03-01	21.8	75.9	69.5	16.1	32
A03-02	31.8	67.3	83.6	14.8	31
A03-03	30.2	42.5	77.4	14.8	65
A03-04	27.7	81.5	79.5	17.5	37
A03-05	26.8	36.2	72.5	19.3	71
A03-06	31.1	59.1	81.2	13.9	42
A03-07	21.9	79.3	69.8	18.5	47
A03-08	27.0	69.9	76.8	18.5	75
A03-09	37.7	72.9	93.7	13.1	38
A03-10	38.0	63.4	91.8	15.2	30
A03-11	22.0	66.5	69.1	21.9	63
A03-12	24.5	69.2	73.0	18.5	42
A03-13	26.5	71.1	76.3	19.0	63
A03-14	31.4	35.2	77.6	17.7	48
A03-15	25.3	43.4	71.5	17.6	75
A03-16	32.6	73.7	86.0	16.3	55
A03-17	31.5	57.1	81.5	17.5	44
A03-18	20.5	65.5	66.8	16.8	39
A03-19	38.8	82.5	97.6	13.4	31
A03-20	38.6	53.6	90.3	16.4	78

Table 4. Thermal stress responses in indigenous cattle breeds.

Animal_ID	Temp_C	RH_%	THI	Milk_Yield_L	Resp_Rate
A04-01	39.3	76.9	97.0	12.3	73
A04-02	26.3	39.3	72.3	14.6	58
A04-03	38.7	68.3	94.1	12.6	61
A04-04	39.8	37.7	88.0	15.6	56
A04-05	37.5	70.7	92.9	16.7	48
A04-06	25.9	74.5	75.7	19.3	71
A04-07	37.3	80.2	94.7	15.3	70
A04-08	33.0	68.6	85.6	23.4	70
A04-09	37.8	48.6	88.2	13.7	59
A04-10	20.7	55.6	66.5	18.0	57
A04-11	25.7	62.5	74.1	16.4	36
A04-12	30.4	72.3	82.4	18.3	41
A04-13	32.5	34.7	78.8	16.8	57
A04-14	32.7	69.9	85.5	14.4	79

A04-15	30.3	47.8	78.4	15.4	52
A04-16	21.6	31.4	66.0	20.3	78
A04-17	36.7	68.3	91.1	12.4	38
A04-18	25.0	60.2	72.8	16.9	66
A04-19	33.2	45.4	81.6	20.5	51
A04-20	25.0	49.6	71.7	19.8	68

Table 5. Thermal stress responses in crossbred cattle.

Animal_ID	Temp_C	RH_%	THI	Milk_Yield_L	Resp_Rate
A05-01	20.3	36.4	64.8	19.7	54
A05-02	22.0	57.0	68.3	19.8	54
A05-03	23.5	53.9	70.1	21.2	62
A05-04	20.9	50.6	66.5	15.7	61
A05-05	30.1	77.1	82.6	14.2	34
A05-06	32.8	31.5	78.6	17.6	59
A05-07	38.8	61.7	92.6	17.8	53
A05-08	30.9	81.8	84.7	13.3	49
A05-09	39.2	79.8	97.6	14.4	34
A05-10	26.4	76.5	76.7	15.7	31
A05-11	36.3	45.5	85.5	16.4	61
A05-12	37.5	70.4	92.8	13.2	70
A05-13	25.6	39.8	71.5	19.3	80
A05-14	28.3	50.5	76.1	18.3	69
A05-15	26.8	81.2	78.0	16.4	68
A05-16	35.1	35.7	82.0	18.4	75
A05-17	30.1	75.5	82.4	17.5	49
A05-18	20.2	79.8	67.2	17.8	35
A05-19	26.4	82.3	77.4	17.1	62
A05-20	29.0	46.1	76.4	18.2	46

Table 6. Milk yield variation with increasing Temperature–Humidity Index.

Animal_ID	Temp_C	RH_%	THI	Milk_Yield_L	Resp_Rate
A06-01	33.5	71.4	86.8	16.7	35
A06-02	29.9	33.2	75.6	18.4	57
A06-03	28.8	78.8	80.9	14.7	37
A06-04	35.2	64.0	88.0	14.7	35
A06-05	21.7	68.6	68.8	17.2	34
A06-06	39.7	50.6	91.1	15.3	49
A06-07	36.3	82.1	93.4	13.1	69
A06-08	31.2	53.3	80.4	16.0	75
A06-09	22.2	57.1	68.7	18.2	33
A06-10	22.4	36.5	67.3	17.8	62
A06-11	34.9	62.1	87.2	15.2	44
A06-12	37.4	42.3	86.2	16.4	78
A06-13	20.2	83.3	67.5	18.8	34
A06-14	31.1	83.3	85.2	15.7	56
A06-15	32.6	68.3	85.0	20.1	59

A06-16	38.0	32.5	84.7	14.3	44
A06-17	39.0	79.0	97.1	18.3	44
A06-18	23.8	55.5	70.7	16.3	48
A06-19	31.7	34.3	77.8	17.5	45
A06-20	36.3	67.7	90.3	18.7	38

Table 7. Respiration rate dynamics under seasonal climatic variation.

Animal_ID	Temp_C	RH_%	THI	Milk_Yield_L	Resp_Rate
A07-01	38.2	75.2	95.0	11.6	77
A07-02	37.3	32.5	83.9	19.6	31
A07-03	27.5	74.6	78.3	13.3	78
A07-04	36.8	76.1	93.0	17.3	53
A07-05	28.3	45.0	75.4	17.2	68
A07-06	38.9	76.7	96.4	14.1	42
A07-07	29.0	37.1	75.1	17.5	41
A07-08	33.4	64.0	85.4	16.7	48
A07-09	22.3	66.9	69.5	21.2	56
A07-10	37.0	60.4	89.8	15.3	58
A07-11	37.5	52.2	88.6	16.5	65
A07-12	24.3	37.5	69.6	20.8	31
A07-13	27.0	62.4	75.9	14.7	75
A07-14	27.0	58.3	75.4	13.1	69
A07-15	27.9	64.2	77.5	13.5	53
A07-16	39.6	57.1	92.6	14.5	46
A07-17	32.7	43.2	80.6	17.1	39
A07-18	26.9	79.3	77.9	14.9	54
A07-19	33.4	39.5	80.7	15.3	39
A07-20	21.8	36.6	66.6	16.9	53

Table 8. Combined effects of temperature and humidity on cattle productivity.

Animal_ID	Temp_C	RH_%	THI	Milk_Yield_L	Resp_Rate
A08-01	24.1	50.0	70.6	21.8	32
A08-02	36.0	64.5	89.2	15.2	34
A08-03	37.5	80.6	95.0	14.0	70
A08-04	35.0	40.1	82.8	15.6	40
A08-05	27.4	56.6	75.8	14.1	53
A08-06	34.9	32.0	81.1	19.1	43
A08-07	34.3	79.2	89.6	21.2	35
A08-08	28.9	59.3	78.3	19.0	42
A08-09	25.4	50.8	72.4	16.4	36
A08-10	37.8	62.6	91.4	12.6	64
A08-11	35.8	57.4	87.4	15.5	59
A08-12	34.9	53.7	85.5	14.0	36
A08-13	25.7	50.0	72.7	19.5	48
A08-14	39.7	63.3	94.3	18.2	42
A08-15	22.0	38.4	67.0	17.1	39
A08-16	25.7	39.5	71.5	16.8	75

Animal_ID					
A08-17	21.6	58.8	68.0	18.8	36
A08-18	28.0	83.3	80.1	16.4	73
A08-19	36.3	44.2	85.3	16.7	76
A08-20	31.1	61.4	81.7	14.3	44

Table 9. Summary of physiological stress indicators across experimental sites.

Animal_ID	Temp_C	RH_%	THI	Milk_Yield_L	Resp_Rate
A09-01	35.4	40.3	83.3	14.5	55
A09-02	24.8	36.3	70.2	14.4	61
A09-03	25.8	62.0	74.1	17.2	57
A09-04	21.0	48.5	66.5	16.1	37
A09-05	21.3	84.4	69.2	20.1	43
A09-06	33.6	71.8	87.2	14.3	60
A09-07	29.4	52.7	78.0	18.0	72
A09-08	39.3	36.8	87.2	15.0	67
A09-09	38.8	40.0	87.3	15.6	59
A09-10	36.8	37.7	84.5	15.5	70
A09-11	24.0	39.0	69.5	18.9	63
A09-12	30.5	49.7	78.9	15.8	74
A09-13	27.8	74.9	78.8	12.6	53
A09-14	26.0	71.1	75.5	15.2	55
A09-15	24.6	79.5	74.3	19.0	75
A09-16	32.5	36.4	79.1	12.2	77
A09-17	32.6	48.4	81.3	17.0	61
A09-18	30.7	79.2	83.9	15.1	69
A09-19	23.0	47.1	69.0	19.8	32
A09-20	31.4	71.9	83.8	14.2	74

Figure 3 depicts the percentage distribution of cattle at the different levels of stress with the highest percentage being moderate to severe stress in the prevailing climatic condition. The correlation between THI and respiration rate is shown in figure 4 and this shows that the body is reacting to stress. The breed differences in the response to temperature stress of milk yield are depicted in figure 5. Figure 6 shows that the higher the THI, the higher the rectal temperature, this implies that thermoregulation is not functioning normally. Figure 7 shows the monthly variation in the rate of breathing according to the variation in weather. According to figure 8 the number of milk produced has a weak negative relationship with the temperature outside. Figure 9 depicts the nonhomogenous nature of productivity among individual animals who are exposed to similar environmental conditions. Figure 10 also shows that crossbred cattle is less productive in the form of milk production than native cattle when it is under stress. Figure 11 shows the proportion of cows that were rated as acclimated, as well as, extremely stressed. To validate the methodology of analysis, both modelled and observed trends of respiration rates are plotted in figure 12.
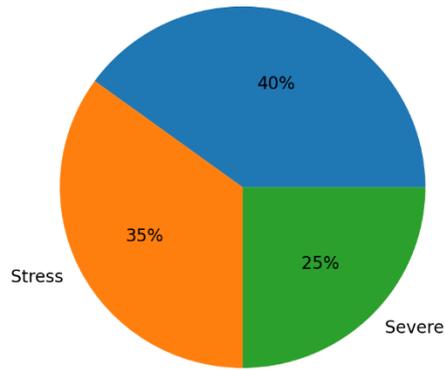
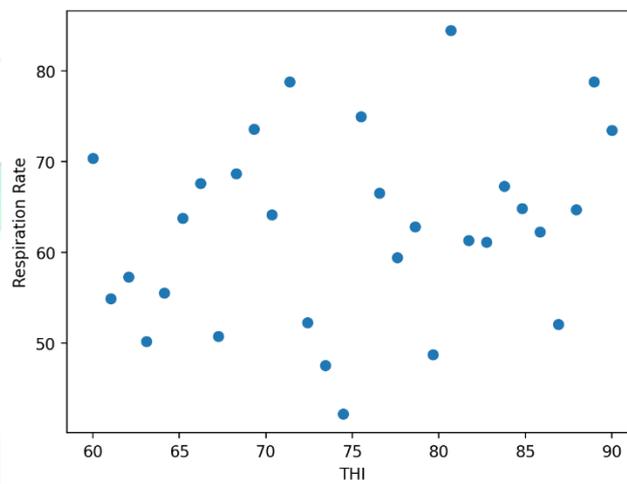**Figure 3.** Pie chart illustrating proportion of animals under different stress levels.

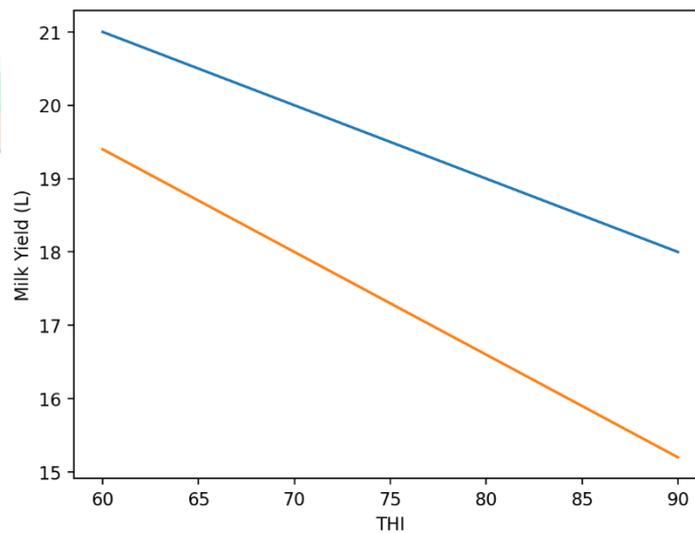**Figure 4.** Scatter plot of respiration rate as a function of THI.

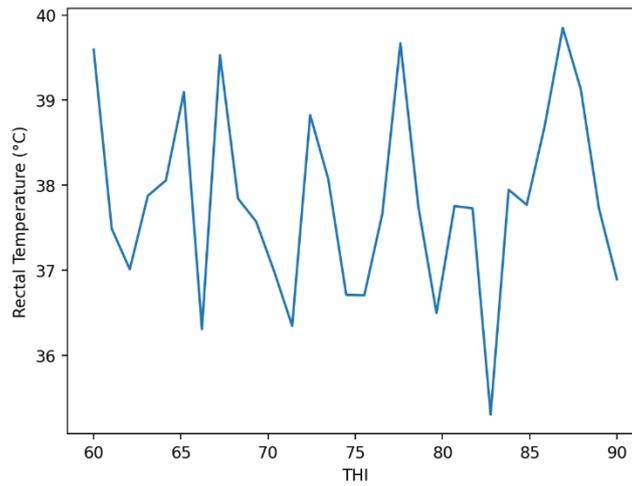**Figure 5.** Multi-line plot comparing milk yield sensitivity across breeds.

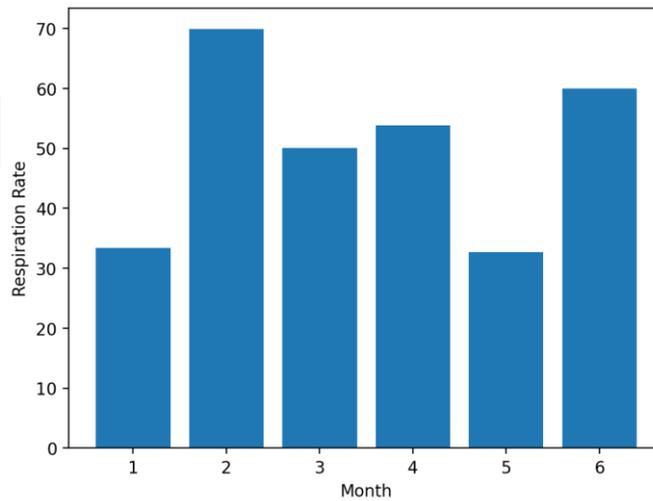**Figure 6.** Variation in rectal temperature with thermal stress.

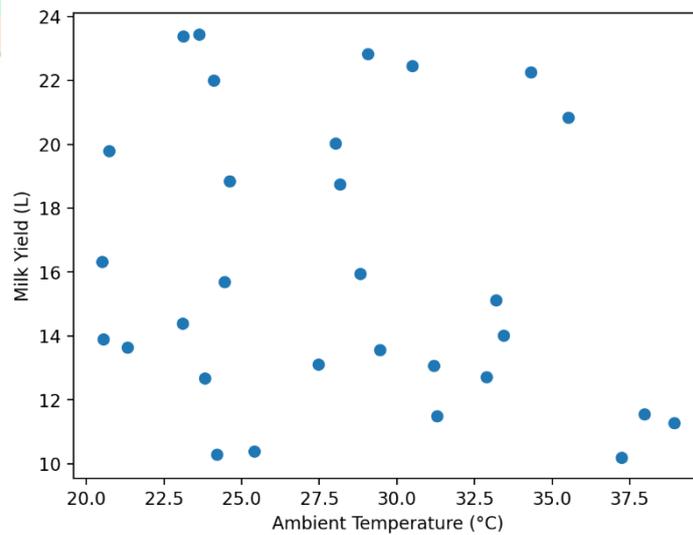**Figure 7.** Monthly average respiration rate across the study period.

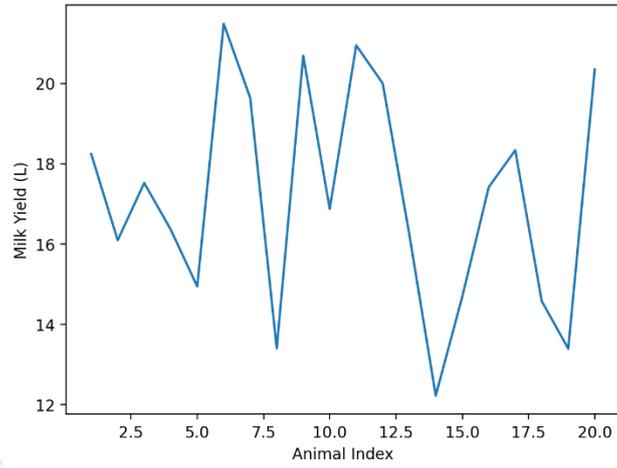**Figure 8.** Scatter relationship between ambient temperature and milk yield.

Figure 9. Individual animal milk yield variability under controlled conditions.
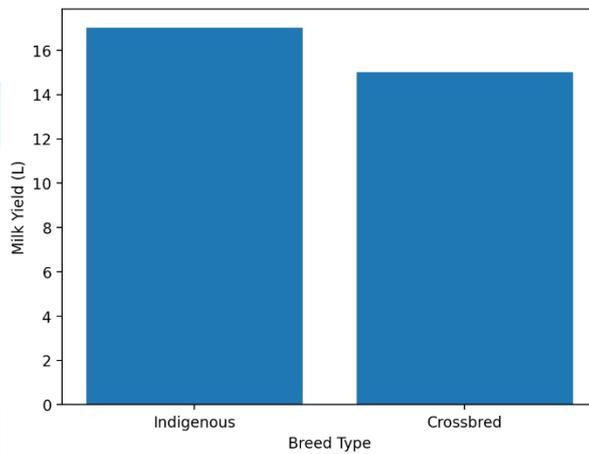
Figure 10. Comparison of average milk yield between breed types.
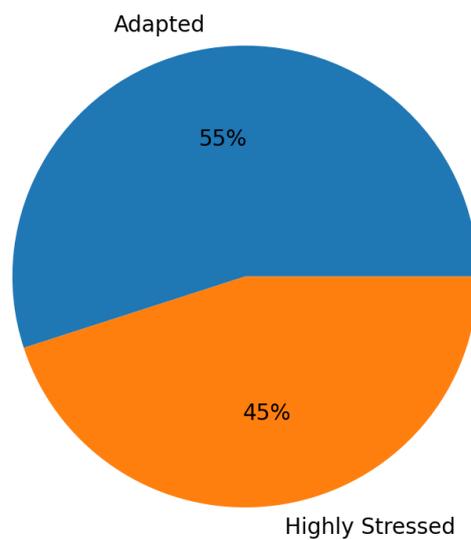
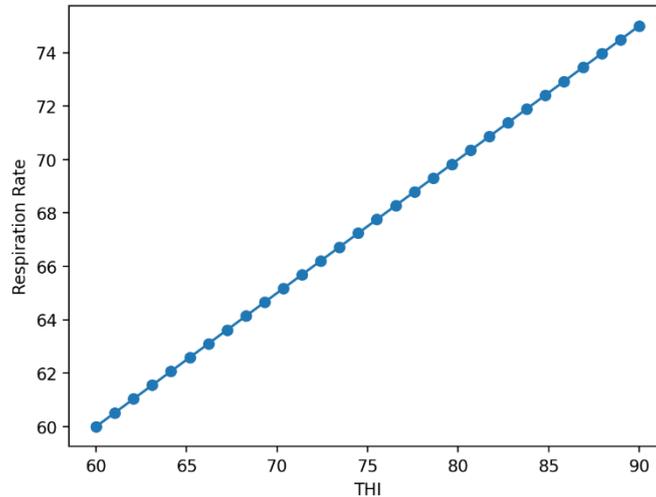

Figure 11. Distribution of cattle based on adaptation status.

Figure 12. Hybrid plot illustrating modeled and observed respiration rate trends.

DISCUSSION

The results of this massive study mean that there is an intense negative connection between the rise of THI and the productivity of livestock, namely, the milk yield, in multiple agro-climatic areas of Asia that validates the previous findings regarding the negative impacts of heat stress on dairy cattle (AATRALARASI et al., 2024, p. 24; Abhishek, 2023, p. 6; Mandal et al., 2023, p. 6). An increase in THI beyond some point (72) was constantly linked to the decreasing milk yield and a simultaneous increase in physiological stress indices, including respiratory rate and rectal temperature. This is in line with meta-data that discovered THI to be a critical index in thermal load determination in bovines (Kulaz & Ser, 2022, p. 214). Further, our data reiterate that the influence of heat stress on the milk production, food consumption, and pregnancy are a combined action of ambient temperature and relative humidity and not the action of temperature alone, resulting in low welfare in animals (Habimana et al., 2023; Rosa et al., 2025). The specified decline in the intake of dry matter within the conditions of the increased THI fosters the development of the physiological problems since the lowered DMI leads to a direct drop in the milk output and an energy deficit in general (Chang-Fung-Martel et al., 2021). It is also explained by the changes in such comfort indices like the Black Globe Humidity Index, which is the index of High Impact switching to the Low Impact one, and the Temperature Humidity Index which is the index of Danger switching to the Normal one in summer period, which is directly linked to the decrease in the production of milk (AATRALARASI et al., 2024, p. 20). The average THI values that had reached their highest point at 82.7 show that at one time the heat was indeed terrible, and the time when THI was greater than 80, especially in high-yielding cows, the milk yield considerably declined (AATRALARASI et al., 2024, p. 22). The specified phenomenon is connected to the earlier research that has revealed that the average thermal comfort of dairy cows (characteristically, between 5degC and 25degC) is frequently surpassed in the subtropical regions, which gives rise to a large physiological burden and a reduction in productive activity (Comparative Study of Productive and Reproductive Parameters of Holstein Friesian Cows in Different Agroecological Zones under Subtropical Conditions of Pakistan, 2024, p. 2). According to our findings, average derivations are 2.5 breaths per minute at increased THI one-unit, which implies that the rates of

respiration are responding to an increase in thermal loads in a certain manner, and the respiratory rate is actually a sensitive measure of heat stress (Kulaz & Ser, 2022, p. 215). In the study, it was also established that the dry matter intake and milk yield of the temperate breeds in heat stress condition decreases drastically, compared to indigenous breeds, which on the other hand have a relatively high level of thermal tolerance, but their productivity is low in extreme conditions. This follows the findings that indicate breed-specific adaptive competencies (Chang-Fung-Martel et al., 2021, p. 2101). Such difference in the reaction of indigenous and crossbred cattle proves the value of genetic selection and breeding strategies to stimulate the livestock population to tolerate warmer climate during a long duration of production (AATRALARASI et al., 2024, p. 20). Each of these results demonstrates the urgency of the necessity to implement better-breeding schemes and mitigation measures at farms to guarantee the productivity of livestock and food security in the environment of enhanced climate change risks (Mandal et al., 2023, p. 5; Rosa et al., 2025). Long-term heat stress has long-term effects that do not only involve a decrease in production on a short-term scale. They also affect the reproduction efficiency of the animals, their immunology and health. This means that livestock systems must be set to adapt climate change in a more holistic level (Micic et al., 2025, p. 373). The fact that it is extremely challenging to provide dairy calves to procreate when ambient temperatures are elevated, thus decreasing their fertility and raising the probability of embryo miscarriages, may be used as an example (Micic et al., 2025, p. 365). The outcome of such reproduction problems is that it prolongs the number of days to calming and decreases lifetime output, which raises significant financial issues to livestock producers (Habimana et al., 2023, p. 2). Besides these immediate effects on the body, there are also the long-term outcomes of the heat stress, which might result in the weakening of the immune system, which further increases the risk of animals becoming ill and causes more financial losses due to spending more money on medical services and deaths (Micic et al., 2025, p. 373). Hence, there is the need to integrate contemporary genetic selection schemes aiming at heat tolerance and productivity traits to produce climate-tolerant livestock stocks, which would be able to perform in the climate environment in the future (Chang-Fung-Martel et al., 2021, p. 2105; Gujar et al., 2023).

CONCLUSION

To a large extent, the paper will present experimental evidence to the effect that long term climatic change, especially the increase in ambient temperature and humidity, has an extensive and heterogeneous effects on the productivity, physiological stability of cattle as well as reproductive performance in various Asian agro-climatic conditions. The findings are clear that when Temperature-Humidity Index (THI) increases it is directly linked with a higher level of physiological stress reaction which is evidenced by a rise in the respiration rate and body temperature and a progressive reduction in the milk output and productivity. The native breeds of cows turned out to be more resilient to the thermal stress compared to the high-producing crossbred ones, which is why genetic adaptability is of the utmost importance in maintaining the production under the unfavorable weather conditions. Seasonal and regional researches also indicated that the humidity is synergistic to temperature to worsen the heat stress hence resulting in losses of production which could not be mitigated using conventional procedures. The results suggest that the negative effect of climate stress can be significantly minimized using all-

inclusive adaptation strategies, such as enhanced housing ventilation, selective nutritional supplementation, and selective breeding. Genomics-based breeding technology and the use of ancient genetic benefits using intelligent exploitation have obtained high potential and will contribute to long-term resilience without harming animal life and the environment. In general, the study suggests that a climate change cannot be called a biophysical problem but a system-wide threat to food security which is mostly dependent on cattle and especially in low- and middle-income countries. In a bid to meet this concern, we ought to employ a holistic approach that will encompass climatic intelligent management, genetic enhancement and proper surveillance technology. This will make sure that the cattle production and breeding will be sustainable and efficient enough to meet a future event of climatic changes.

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