

**Unveiling the Impacts of Climate Change Induced Heat Stress
on Dairy Farming in Chakwal District**



By

Safia Bibi

Reg. No: 966-FBAS/MSES/F23

Department of Environmental Science

Faculty of Sciences

INTERNATIONAL ISLAMIC UNIVERSITY ISLAMABAD

Spring 2025

Unveiling the Impacts of Climate Change Induced Heat Stress on Dairy Farming in Chakwal District



Supervisor:
Dr. Sarah Amir
Lecturer, DES, IIUI

Researcher:
Safia Bibi
966-FBAS/MSES/F23

Department of Environmental Science

Faculty of Sciences

INTERNATIONAL ISLAMIC UNIVERSITY ISLAMABAD

Spring 2025

بِسْمِ اللَّهِ الرَّحْمَنِ الرَّحِيمِ

Department of Environmental Science
International Islamic University, Islamabad

Dated-----

FINAL APPROVAL

It is duly certified that we, the esteemed evaluators, have thoroughly reviewed the thesis submitted by Ms. Safia Bibi. We declare and affirm that this thesis meets the sufficient standard for its approval by the International Islamic University, Islamabad for the MS Degree in Environmental Science.

COMMITTEE

External examiner

Internal examiner

Supervisor

Dr. Sarah Amir

Lecturer/Incharge Academic Affairs

Department of Environmental Science

International Islamic University Islamabad

Chairperson, DES

Dr. Syeda Maria Ali

International Islamic University Islamabad

Dean, FoS

Dr. Muhammad Mushtaq Ahmed

International Islamic University Islamabad

A thesis submitted to the Department of Environmental Science, International Islamic University Islamabad as a partial fulfillment of the requirement for the award of the degree of MS Environmental Science.

DEDICATION

In the Name of Allah, The Most Beneficent and The Most Merciful. I express my gratitude to Allah Almighty for His abundant blessings and kindness enabling me to successfully and enthusiastically complete my MS research work. This research is a heartfelt dedication to my beloved Parents, and my esteemed Supervisor, Dr. Sarah Amir. Their unwavering support, affection, and cordial prayers have been a constant source of inspiration and encouragement throughout my journey.

DECLARATION

I, Ms. Safia Bibi, enrolled as an MS Environmental Science student (Registration #966-FBAS/MSES/F23), solemnly affirm that the work presented in the thesis titled “Unveiling the Impacts of Climate Change Induced Heat Stress on Dairy Farming in Chakwal District” is the result of my independent endeavor, except where otherwise acknowledged and that the thesis is my own composition. No part of the thesis has been previously presented for any other degree. I extend my gratitude to the management and staff of the Daim dairy farm in Chakwal district Pakistan, whose invaluable support and cooperation have facilitated the execution of this work.

TABLE OF CONTENTS

ACKNOWLEDGEMENTS	i
LIST OF ABBREVIATION	ii
LIST OF TABLES.....	iv
LIST OF FIGURES.....	v
ABSTRACT	v
CHAPTER 01	1
1. Introduction	1
1.1 Background	1
1.2 Global Challenges of Climate Change.....	1
1.3 Vulnerability of the Agricultural Sector	2
1.4 The Critical Role of Livestock and the Dairy Sector	3
1.5 Heat Stress as a Key Challenge for Dairy Cattle	3
1.6 Global Heat Stress Challenge	5
1.7 Asian Dairy Sector Vulnerability	5
1.8 Pakistan's Herds under Climate Stress	6
1.9 Problem Statement	9
1.10 Aim and Objectives of the Study	9
1.11 Significance of the Study	9
1.12 Scope and Limitations of the Study	10
CHAPTER 02	1
2. Literature Review.....	11
2.1 Climate change: causes and regional impacts	11
2.2 Heat waves under climate change	12
2.3 Impact of heat stress on livestock and agricultural sustainability	14
2.4 Heat stress in dairy cattle.....	13
2.5 Heat stress thresholds and their effects on milk yield and composition	13
2.6 Climate change and livestock-dependent livelihoods	12
2.7 Global dairy production under climate stress.....	13

2.8	Livestock vulnerability in developing nations.....	13
2.9	South Asia’s livestock sector in a changing climate	13
2.10	Pakistan’s dairy Sector	13
CHAPTER 03		22
3.	Materials and Methods	23
3.1	Study Area	23
3.2	Experimental Farm Characteristic	24
3.2.1	Farm Selection and Characteristics.....	24
3.2.2	Animal Selection Criteria.....	24
3.3	Experimental Design.....	24
3.4	Data Acquisition.....	26
3.4.1	Environmental Data	27
3.4.2	Milk Production and Composition Data	27
3.4.3	Physiological Data	27
3.5	Statistical Analysis.....	28
3.5.1	Descriptive Statistic	28
3.5.2	Correlation Analysis	28
3.5.3	T-test for Seasonal Comparison.....	29
3.5.4	Regression Analyses	29
CHAPTER 04		33
4.	Results.....	30
4.1	Characterization of Environmental Conditions	30
4.2	Milk Yield Patterns and Distribution.....	34
4.3	Weekly Heat Stress and Production Trends	35
4.4	Dominant Influence of Humidity	36
4.5	External Environment and Milk Yield	37
4.6	Shed vs. Outdoor Environment.....	40
4.7	Simple Linear Regression Analysis of Humidity on Milk Yield	42
4.8	Multivariate Analysis of Stressors	43
4.9	THI's Inadequate Production Prediction	45

4.10	Pearson Correlation Matrix of Environmental and Production Variables	46
4.11	Rectal Temperature as a Partial Mediator	48
4.12	Milk Composition Stability Under Stress	50
4.13	Seasonal Micro environmental Impact Analysis	50
4.14	Seasonal Thermal Environment Effects	51
4.15	Pearson Correlations between Environmental Variables and Milk Yield, by Season.	54
4.17	Weekly Analysis of Seasonal Production Variability	57
4.18	Seasonal Comparative Analysis of Dairy Production Parameters	58
4.19	Differential Seasonal Correlation Patterns in Dairy Parameters	61
CHAPTER 05		63
5.	Discussion	64
CHAPTER 06		67
6.	Conclusion	68
6.1	Recommendations.....	71
References		73

ACKNOWLEDGEMENTS

First of all, thanks and praises to Allah Almighty - The Compassionate, The Merciful, who granted us health, wisdom, strength, and the ability to do the tasks assigned to us. I have the utmost regard for Hazrat Muhammad (PBUH), the light of enlightenment and torch of guidance for mankind.

I would like to express my deepest gratitude and sincere thanks to my honorable Supervisor Dr. Sarah Amir, Incharge Academic Affairs/Lecturer, Department of Environment Science, International Islamic University, Islamabad, for her keen interest, providing her precious time, valuable guidance, and moral support throughout my research work. It was a great privilege for me to study and work under her supervision.

I would like to express my heartfelt gratitude to my beloved father Muhammad Iqbal and my lovely mother Noor Begum who are my strongest supporters. Their belief in me has been a driving force in my life. I couldn't achieve anything without their constant love and support.

LIST OF ABBREVIATIONS

Acronym	Abbreviations
CBT	Core Body Temperature
CC	Climate Change
CCI	Comprehensive Climate Index
CH ₄	Methane
DCP	Dicalcium Phosphate
FPCM	Fat and Protein Corrected Milk
GDP	Gross Domestic Product
GHGs	Greenhouse Gases
GtCO ₂	Gigatonnes of Carbon Dioxide
GtCO _{2e}	Gigatonnes of Carbon Dioxide Equivalent
HFCs	Hydro fluorocarbons
HS	Heat Stress
IPCC	Intergovernmental Panel on Climate Change
N ₂ O	Nitrous Oxide
NVBs	Natural Ventilated Barss
PFCs	Perfluorocarbons
PMD	Pakistan Meteorological Department
R&D	Research and Development
SDGs	Sustainable Development Goals
SF ₆	Sulfur Hexafluoride
SNF	Solids-Not-Fat
THI	Temperature-Humidity Index
TMR	Total Mixed Ration
UNEP	United Nations Environment Programme
UNFCCC	United Nations Framework Convention on Climate Change

LIST OF FIGURES

Figure 3.1: Study area map showing the geographical location of Chakwal, Pakistan.....	24
Figure 4.1: Linear relationship between internal shed humidity and total daily milk yield.....	29
Figure 4.2: Milk yield comparison across Temperature-Humidity Index Categories.....	31
Figure 4.3: Conceptual framework for mediation analysis.....	34
Figure 4.4: Results of mediation analysis showing humidity effects through rectal temperature.	34
Figure 4.7: Seasonal comparison of milk production under heat stress.....	50
Figure 4.8: Simple scattered plot between milk yield and THI by seasons.....	56

LIST OF TABLES

Table 3.1: Feed ingredients and chemical composition of the concentrated diet.....	24
Table 4.1: Characterization of Environmental Conditions.....	25
Table 4.2: Milk Yield Patterns and Distribution.....	26
Table 4.3: Weekly Heat Stress and Production Trends.....	26
Table 4.4: Dominant Influence of Humidity.....	27
Table 4.5: External Environment and Milk Yield.....	27
Table 4.6: Paired Samples Comparison Internal Vs. External Environmental Parameters.....	28
Table 4.7: Simple Linear Regression Analysis of Humidity on Milk Yield.....	28
Table 4.8: Multivariate Analysis of Stressors.....	29
Table 4.9: Descriptive Statistics of Milk Yield by Heat Stress Category.....	30
Table 4.10: One-Way ANOVA Results for Heat Stress Categories.....	30
Table 4.11: Post-hoc Comparisons (Tukey HSD)	30
Table 4.12: Pearson Correlation Matrix of Environmental and Production Variables.....	32
Table 4.13: Rectal Temperature as a Partial Mediator.....	33
Table 4.14: Model Summary for Mediation Analysis.....	33
Table 4.15: Simple Linear Regression Analysis of Humidity on Milk Quality Parameters.....	35
Table 4.16: Seasonal Micro environmental Impact Analysis.....	47
Table 4.17: Seasonal Thermal Environment Effects.....	48
Table 4.18: Seasonal Correlation Analysis by Seasons.....	49
Table 4.19: Seasonal Environmental Predictors of Milk Yield.....	51
Table 4.20: Weekly Analysis of Seasonal Production Variability.....	52
Table 4.21: Seasonal Comparative Analysis of Dairy Production Parameters	53
Table 4.22: Differential Seasonal Correlation Patterns in Dairy Parameters	54

ABSTRACT

Climate change-induced heat stress poses a significant threat to dairy productivity, a critical concern for food security and rural livelihoods in semi-arid regions. In the Chakwal District of Punjab, Pakistan, increasing temperatures and humidity levels are exacerbating thermal stress on dairy cattle, yet region-specific impacts on production and effective mitigation strategies remain inadequately studied. This research aimed to quantify the impact of seasonal heat stress on milk yield and composition in a high-management dairy herd and to identify the dominant environmental drivers of production loss. The study employed an observational, longitudinal design to monitor 50 lactating Holstein Friesian cows across two distinct climatic periods: the high heat-stress summer (June–July) and the low heat-stress winter (November–December) of 2025. Data on environmental parameters (temperature, humidity, Temperature-Humidity Index - THI), daily milk yield, weekly milk composition (fat, lactose, solids-not-fat), and physiological data (rectal temperature) were collected and analyzed using correlation, regression, ANOVA, and mediation analysis. The results identified internal shed humidity as the dominant environmental stressor, exhibiting a strong negative correlation with milk yield ($r = -0.82$, $p < 0.01$) and accounting for 66.5% of its variance ($R^2 = 0.665$). The regression model quantified a significant production loss, with milk yield decreasing by 4.38 liters per day for every 1% increase in humidity. The standard Temperature-Humidity Index (THI) was found to be an inadequate predictor of these losses. A severe 23.9% reduction in milk yield was observed in summer compared to winter. While yield was significantly affected, milk composition remained stable. Mediation analysis revealed that rectal temperature acted as a significant partial mediator, explaining 24.4% of humidity's total impact on yield, thereby illustrating the physiological pathway of energy diversion from milk synthesis to thermoregulation. The study concludes that in the semi-arid climate of Chakwal, managing microclimatic humidity is more critical than temperature alone for mitigating heat stress in dairy cattle. The findings advocate for a shift in management focus toward active humidity control in cattle housing. Recommendations include farm-level interventions such as optimized ventilation, the development of localized climate indices that prioritize humidity, and enhanced policy support for climate-resilient dairy infrastructure. This research aligns with key Sustainable Development Goals (SDGs), notably SDG 2 (Zero Hunger) by supporting sustainable food production and SDG 13 (Climate Action) by promoting adaptive agricultural practices. Future studies should investigate genetic traits for humidity tolerance and long-term adaptation strategies

to bolster the sustainability of the dairy sector in climate-vulnerable regions.. Recommendations include farm-level interventions for humidity control, development of localized climate indices, and policy support for climate-resilient dairy infrastructure.

CHAPTER 1

INTRODUCTION

Chapter 1

1. Introduction

1.1 Background

Addressing the rapid and widespread consequences of climate change has become one of the most urgent and complex challenges confronting the global community today. Climate change refers to substantial and lasting shifts in the average patterns of weather variables such as temperature and rainfall which have profound implications for ecosystems, economies and societies worldwide (Malhi et al., 2021). Apart from unusual weather patterns, climate change is clearly demonstrated by the swift melting of ice sheets across the globe and the consequent elevation in sea levels with impacts felt both internationally and locally (Abbass et al., 2022).

At present, anthropogenic factors are seen as the leading contributors to climate change (Murshed et al., 2022). Besides the industrial revolution, climate change is fueled by a range of human activities, including high-intensity agriculture using fossil-fuel machinery, residue burning, deforestation and transport emissions. These activities result in climate disasters that threaten infrastructure, health and productivity worldwide. The situation is especially critical in developing countries, where fossil fuels remain the primary energy source significantly increasing greenhouse gas emissions (Abbass et al., 2021a; Lorente et al., 2022; Ishiwata & Furuya, 2022; Usman et al., 2022b).

1.2 Global Challenges of Climate Change

The interior regions of the continent are likely to be impacted by rising temperatures (Kamruzzaman et al., 2023). It is projected that the global mean surface temperature will rise by approximately 3.7°C (with a likely range of 2.6°C to 4.8°C) by 2100, accompanied by changes in the frequency, intensity and duration of extreme weather events (Ali et al., 2020). As temperature is widely regarded as the most significant environmental factor among bioclimatic variables that induce stress in organisms. The interaction between temperature and relative humidity contributes to the onset of heat stress (Kumar et al., 2021). The impact of high temperatures becomes more severe when accompanied by high ambient humidity, as the reduced efficiency of evapotranspiration limits the dissipation of heat (Slimen et al., 2020). Heatwaves, droughts and floods can negatively affect food security, health and nutrition while

also lowering work productivity and threatening the livelihoods and incomes of people especially those working outdoors or in sectors that are highly sensitive to climate conditions (Mirzabaev et al., 2023). As a major environmental threat of the 21st century, climate change poses a growing global challenge.

1.3 Vulnerability of the Agricultural Sector

Climate change poses a serious threat across various sectors, but its impact on agriculture, the cornerstone of global food security and a vital contributor to economic stability stands out as especially critical. As one of the most climate-sensitive industries, agriculture is highly susceptible to environmental fluctuations due to its intense reliance on and sensitivity to varying environmental and hydrological conditions. The sector not only ensures food supply but also supports employment, feeds manufacturing through raw material provision and contributes significantly to foreign trade through export revenues (Ahmad & Afzal, 2021).

The effects of climate change on agriculture vary from region to region, influenced by local manifestations of climatic shifts, which threaten both global food production and food security (Guo et al., 2022). Projections for the future indicate that some agricultural systems may see enhanced productivity due to warmer climates, more rainfall and elevated CO₂ levels. In contrast, other systems may face adverse impacts where existing crops or varieties become unsuitable, necessitating significant changes in cultivation methods or the introduction of alternative crops (Volk et al., 2023).

Research increasingly shows that agriculture, a sector heavily dependent on stable environmental conditions is suffering under the pressures of climate change. Shifts in climate ranging from erratic rainfall and soaring temperatures to more extreme weather events, higher carbon dioxide levels and rising seas are disrupting both crop cultivation and livestock systems (Chien & Pantamee, 2021; Nawaz et al., 2021). It influences food systems in various ways, such as lowering crop yields, causing livestock deaths and triggering indirect effect like unstable food prices and disrupted market supplies. These effects are especially concerning in regions where rain-fed agriculture remains the main source of food and income (Muluneh, 2021).

1.4 The Critical Role of Livestock and the Dairy Sector

Livestock, a key component of agriculture, significantly contributes to global food security by providing about 33% of protein and 17% of calorie intake. With the global population expected to rise, the demand for livestock products is projected to increase by 70% by 2050—a trend often referred to as the “livestock revolution” in developing countries. Milk production is forecasted to rise from 811 million tons in 2017 to 1,077 million tonnes by 2050 while meat consumption is expected to grow by 76% outpacing cereal consumption. Livestock also plays a vital economic role in supporting rural households, particularly for smallholder farmers, agro-pastoralists and pastoralists (Shahbaz et al., 2020).

Various stressors affect livestock, impacting their ability to produce, reproduce and stay healthy. Heat stress from environmental changes is currently a major issue, particularly for animals with high productivity as it can severely impair their performance. In arid and semi-arid areas, the livestock industry is highly susceptible to the effects of rising temperatures and decreasing rainfall. Livestock perform best within a temperature range of 10–30°C. When temperatures rise above this range each 1°C increase can cause a 3–5% drop in feed intake while colder conditions may increase animals' feed needs by up to 59%. A climate change-driven drought and heat stress are projected to greatly reduce livestock productivity (Rahman et al., 2022).

1.5 Heat Stress as a Key Challenge for Dairy Cattle

Climate change impacts dairy production both directly by affecting the animals themselves and indirectly. Environmental stressors resulting from climate change represent a critical challenge for livestock systems worldwide. For ruminants, increased atmospheric CO₂ and ambient temperature deteriorate forage quality by modifying plant biochemical composition and reducing digestibility. Drought conditions further reduce feed availability and nutritional density. While flooding degrades soil fertility and lowers crop yields. Consequently, livestock may fail to meet nutritional requirements essential for metabolic functions, reproduction and productivity. Moreover, global warming facilitates the survival and geographic expansion of vector-borne pathogens introducing additional risks to animal health (Cartwright et al., 2023).

Heat stress poses significant welfare and economic challenges for the livestock sector and is projected to remain a pressing issue due to the continued rise in atmospheric greenhouse gas

levels. Among various livestock species dairy cattle are particularly vulnerable with the dairy industry experiencing the most substantial economic losses associated with heat stress. Prolonged exposure of lactating dairy cows to high temperatures, humidity and solar radiation hampers their ability to regulate body heat increasing the risk of heat stress. Warmer and drier conditions exacerbate this stress by negatively influencing reproductive performance of dairy animals (Frigeri et al., 2023). Consequently, identifying traits that confer resilience to high temperatures has become a critical research focus.

Heat tolerance is the capacity of an animal to sustain its inherited performance levels under high-temperature conditions. Key physical characteristics that support heat tolerance include a large skin-to-body weight ratio, pigmented eyelids and skin protective eye features and a light or white-colored coat. Animals that are adapted to hot environment should also be capable of traveling long distances, surviving on limited water tolerating high salt levels in water or forage and coping with low-quality feed (Chen et al., 2023).

Animals regulate homeostasis by processing internal and external information crucial for growth and productivity. Exposure to high temperatures, humidity and solar radiation disrupts these mechanisms with native species being more thermo tolerant than exotic species due to evolutionary advantage. Lactating cattle use up to 31% of their energy for metabolic functions as heat. When exposed to high temperatures their energy expenditure can increase by 20%, leading to heat stress (Moore et al., 2023).

Under heat stress dairy cows display various physiological changes such as reduced feed intake, increased energy needs for maintenance, lower milk yield and changes in milk composition. Continuous exposure to high heat and humidity leads to decreased milk quantity and quality. As a result, dairy farming is becoming increasingly vulnerable to climate change leading to a decline in productivity due to ongoing climate variability (Montcho et al., 2022). Thus, the Temperature-Humidity Index (THI) is commonly employed to assess heat stress in dairy cattle.

The specific Temperature-Humidity Index (THI) value that marks the heat stress threshold for dairy cattle varies, typically ranging from 60 to 78 THI units, and is influenced by regional climates and herd productivity levels. The evaluation of thermal comfort using the THI is well-researched and common; this index combines air temperature and relative humidity, differently weighted, into a single unitless value. Other climatic indices used to assess heat stress (HS) in dairy cows include the heat load index, thermal stress index, dairy heat load index, and Comprehensive Climate Index (CCI). However, these indices are less commonly used, while the THI remains the most widely adopted

measure for heat stress in dairy cows (Mbuthia et al., 2022).

1.6 Global Heat Stress Challenge

In the U.S. livestock industry, economic losses due to heat stress are estimated to amount to billions of dollars annually with dairy cattle being the most severely impacted group (Theusme et al., 2021). Climate change poses significant challenges to animal physiology, welfare, health and reproduction with profound implications for livestock production. Key impacts include the rising frequency of hot days, prolonged heat waves, extended warm spells, and an increase in extreme weather events all of which critically affect the well-being and productivity of animals (Gauly & Ammer, 2020). Dairy cows productivity is maximized when they are stress-free and able to adapt to environmental factors like temperature, humidity, wind and sunlight (Venegas et al., 2023).

The ongoing climate change, combined with the rising demand for livestock products creates a significant challenge. Effectively addressing this issue requires a clear understanding of how climate change affects livestock production along with the potential outcomes of both adaptation and mitigation strategies (Cheng et al., 2022). Adaptation strategies for dairy production to climate change involve a range of actions including adjustments in feeding, health management, breeding and shelter practices to optimize animal welfare and productivity (Kom et al., 2022). However, current knowledge of the vulnerability factors at the farm level and the adaptation processes remains limited particularly in developing countries due to a lack of research on environmental vulnerabilities and the stimuli that drive adaptation (Tofu et al., 2023).

1.7 Asian Dairy Sector Vulnerability

In Asia, the livestock sector engages about 60% of the population and contributes 25% to the Gross Domestic Product (GDP). Over the past 25 years, Asia has seen considerable advancements in tackling food insecurity. Researchers highlight that the growth in agricultural productivity across many Asian countries is largely driven by technological innovations supported by research and development (R&D) in agriculture as well as improvements in human capital (Ozdemir, 2022). While climate change poses a serious threat to agricultural sustainability in South Asia where farming practices are less technologically advanced compared to developed nations (Wankar et al., 2021). In Bangladesh, the livestock sector faces increasing vulnerability to climate change with heat stress, disease outbreaks and metabolic disorders significantly affecting livestock health. Adapting to changing climatic conditions is

the best approach to mitigate the harmful effects of climate change and protect the agricultural sector.

India accounts for 23% of global milk production and continues to see rapid growth in the sector. Its milk production is increasing at over 6% annually, which is significantly higher than the global average of 2%. Traditionally dairy farming has served as a supplementary livelihood for marginal and landless farmers in India. However, in recent decades it has gained prominence among larger farming households as well. Despite this progress, the Indian dairy industry is now confronting mounting challenges due to climate change. Unpredictable weather patterns, especially in semi-arid southern regions affected by irregular rainfall and prolonged droughts have disrupted dairy operations. These climate-related stressor threaten the sustainability of rural livelihoods and add uncertainty to dairy farming across much of the country (Shantharaju et al., 2024).

1.8 Pakistan's Herds under Climate Stress

Pakistan ranks among the most climate-sensitive countries, despite contributing only 0.8% to global greenhouse gas emissions and being 135th in global emissions. Located in a region where temperature rises are expected to exceed the global average, Pakistan faces rapidly melting glaciers, widespread arid and semi-arid land and unpredictable weather. With more than 40% of its population relying on agriculture the country is highly exposed to climate risks like erratic monsoons, floods and droughts. These factors together threaten Pakistan's food, water and energy security (Khan et al., 2020). According to the Global Climate Risk Index, Pakistan ranks among the most vulnerable countries globally. The index ranked Pakistan 5th for the year 2022, and it was the 4th most affected nation over the two-decade period from 2003 to 2022, underscoring its persistent high vulnerability.

Pakistan is among the most vulnerable nations to the impacts of heatwaves which typically occur between May and September and can reach temperatures exceeding 50 °C (Rana et al., 2022). The devastating heatwave of 2015 in Karachi alone resulted in over 1,200 fatalities and approximately 65,000 heat-related illnesses. In Pakistan, a heatwave is officially defined as a period during which the daily maximum temperature exceeds the historical average by 5 °C or more for five or more consecutive days based on the 1961–1990 reference period (Ullah et al., 2024).

Pakistan's agriculture sector contributes to the economy in two major ways: by feeding the

population and by boosting economic stability through reduced food imports. It provides essential raw materials for industries with cotton being a key export and a backbone of the textile industry. The sector also supports animal husbandry by supplying feed for dairy and meat-producing animals. In fact, most sectors of the economy are interconnected with agriculture for their raw material supplies (Shafiq et al., 2021). More than 60% of people in Pakistan live in rural areas and most of them rely on farming and related work for their income (Abbas et al., 2024). Livestock is one of the most important parts of agriculture making up 60.56% of agricultural GDP and 11.69% of the country's total GDP with a growth rate of 2.58%. Over 8 million families in rural Pakistan raise animals to earn a living (Faisal et al., 2021).

Pakistan's dairy sector is typically categorized into small-scale, mid-sized and corporate farms distinguished by their management practices, herd sizes and levels of milk production. The majority of livestock comprising 30 million cattle, 27 million buffaloes, 54 million goats, 27 million sheep and 1 million camels is owned by rural households with more than 8 million small-scale farmers across the country. However, these farmers often focus solely on meeting their household dairy needs and tend to overlook the economic opportunities offered by improved livestock management. As a result, between 2014 and 2017 Pakistan had to import 185,749 metric tons of packaged liquid milk worth 50 billion Pakistani rupees (around 474 million US dollars) just to meet the needs of the public (Shahzad, 2022).

For over a decade corporate dairy farms in Pakistan have been run by business owners. Each farm usually has 2,000 to 6,000 imported, high-yielding animals and around 16 farms are operating nationwide. These farms often known as elite farms achieve milk production of 25–35 liters per cow per day at peak and their total daily milk production can reach between 20,000 and 100,000 liters. They use advanced tools and proper management systems and are well-organized in feeding and operations. The milk is sold either to big dairy companies or processed in their own units. Cows that are not productive are regularly replaced. But the challenge of heat stress in livestock farming is becoming an increasingly important concern (Farhan et al., 2024).

Ranked among the world's top five milk producers, Pakistan's dairy sector plays a key role in combating hunger, lowering poverty levels and supporting economic growth. But numerous studies in the country have highlighted the significant impact of climate change on crop production with less focus on particularly dairy farming (Abbas et al., 2022). Cattle, buffalo, sheep and goats are the primary livestock species in Pakistan. Among these, cattle and goats demonstrated the highest growth rates between 2018 and 2021, whereas buffalo and sheep

experienced comparatively slower growth during the same period (MOF Pakistan, 2020; Mehmood et al., 2022).

Future climate projections indicate significant warming trends in Punjab, Pakistan particularly across the Kharif and Rabi agricultural seasons. By mid-century (2040–2069), projections indicate that Kharif season temperatures will rise, with maximum temperatures increasing by 1–3.3 °C and minimum temperatures by 2–3 °C. For the Rabi season, projections show maximum temperatures rising by 2.1–3.5 °C and minimum temperatures by 2–3 °C. Simulations also suggest 25–35% variability in rainfall during the Kharif season, whereas Rabi rainfall patterns will remain relatively stable. These trends highlight a consistent increase in both temperature extremes and precipitation variability in the Punjab (Malhi et al., 2021)

As the most populous and agriculturally productive province, Punjab holds a central position in Pakistan's economic and demographic landscape. In Pakistan, Punjab a rain-fed regions play a vital role contributing approximately 80% of the country's livestock production. In areas like Chakwal a region where dairy farming is integral to rural livelihoods is increasingly affected by climate variability. Fluctuating temperatures, unpredictable rainfall and frequent heatwaves have begun to compromise milk production and animal well-being. Due to its semi-arid climate the district remains highly susceptible to climate-induced stress, highlighting the need for urgent evaluation and adaptive strategies (Mylostyvyi et al., 2023).

This study assessed the impact of heat stress on milk production in dairy cows by employing the Temperature-Humidity Index (THI), a widely recognized indicator used to quantify thermal stress in livestock. By correlating THI levels with changes in milk yield, the research will provide valuable insights into how increasing temperatures and humidity (key symptoms of climate change) are affecting dairy productivity in the region. The Sustainable Development Goals (SDGs) serve as a global call to action aimed at protecting the earth and ensuring peace and prosperity for all. Because they are interconnected these goals strive to balance environmental, social, and economic aspects of sustainable development. Among the 17 goals, seven are directly related to issues in agriculture and climate change (Grigorieva et al., 2023). This research aligns closely with the United Nations Sustainable Development Goals (SDGs), particularly SDG 2 (Zero Hunger), by aiming to enhance food security through improved livestock productivity, and SDG 13 (Climate Action), by addressing the need for adaptive strategies in agriculture to cope with climate change. Ultimately, the study seeks to support sustainable rural livelihoods and strengthen the resilience of the dairy sector in climate-vulnerable regions like District Chakwal.

1.9 Problem Statement

The increasing variability in weather patterns driven by global climate change poses a significant challenge to dairy farming particularly in developing countries that are facing unpredictable and extreme climate fluctuations. This is particularly concerning for regions like Chakwal District which is a rain-fed agricultural area highly susceptible to the adverse impacts of climate change. Chakwal's proximity to Islamabad and Rawalpindi (approximately 100 km) facilitates dairy product transportation to urban markets. However, the dairy sector in Chakwal faces increasing risks due to rising temperatures and more frequent extreme weather events. Heat stress in particular has become a critical concern leading to reduce feed intake, decreased milk yield and higher mortality rates among livestock. According to surveys a majority of farmers over 60% observed a substantial decrease in individual animal productivity in peak summer, with daily milk output falling by 20 to 40 percent. Limited studies have addressed the potential impacts of climate change-induced heat stress on dairy cattle in Pakistan. While several studies on climate change adaptation in dairy farming have been conducted in various districts of Punjab but Chakwal an important region for dairy farming has been notable absent from such studies. Moreover, existing studies have largely neglected the impact of climate change-induced heat stress on milk production In Pakistan, heat stress is estimated to cause annual economic losses exceeding PKR 80 billion (approximately \$287 million) in the dairy sector. Therefore, this study seeks to fill this gap by specifically focusing on District Chakwal and investigating the effects of heat stress on dairy productivity.

1.10 Aim and Objectives of the Study

This study assessed the impact of climate change-induced heat stress on milk production in District Chakwal. The study focused on the following specific objectives to achieve this aim:

- To evaluate the impact of heat stress on milk yield and compositional quality parameters in milk.
- To investigate seasonal fluctuations in environmental factors and their relationship with variations in milk yield and composition in dairy cattle.

1.11 Significance of the Study

This study is significant due to its focus on District Chakwal, a critical livestock

production hub that has been largely neglected in research on impacts of climate change on dairy productivity. By exploring the specific challenges faced by livestock farmers in this region, particularly regarding heat stress and its impact on dairy productivity the research will provide valuable insights into how climate change affects livestock farming in this context. This study will offer potential solutions to enhance farm management practices, increase livestock productivity and improve profitability in the face of climate-induced challenges. Furthermore, this research will contribute to the academic literature on climate change adaptation in agriculture by shedding light on the specific climate stressors affecting dairy farming in Pakistan's rain-fed areas. It will also offer practical recommendations for residents of Chakwal helping farmers manage heat stress to improve livestock health, increase milk production and enhance overall farm productivity thereby improving livelihoods. Additionally, the findings provide valuable data that can inform policymakers and agricultural extension services, helping to design region- specific evidence-based policies and programs that promote climate-resilient farming practices. This study guides sustainable livestock farming in regions vulnerable to climate change, ensuring better socio-economic outcomes for farmers.

1.12 Scope and Limitations of the Study

This study was scoped to investigate climate change-induced heat stress impacts within the specific context of a single, high-management commercial dairy farm in Chakwal District, focusing exclusively on 50 lactating Holstein Friesian cows monitored across summer and winter seasons, with analysis limited to environmental parameters (temperature, humidity, THI), milk yield, basic composition (fat, lactose, SNF), and rectal temperature as the primary physiological indicator. However, the findings are constrained by several limitations: the single-farm, single-breed design limits generalizability to small-scale or traditional farms with different management practices and indigenous breeds; the exclusion of other heat stress indicators like respiration rate, feed intake, and animal behavior restricted a comprehensive physiological assessment; the short-term observational nature of the study could not account for long-term adaptive responses or cumulative effects of heat stress; and the focus on a farm with existing cooling infrastructure may underestimate the severity of impacts on farms without such resources.

CHAPTER 2

LITERATURE REVIEW

Chapter 2

2. Literature Review

2.1 Climate change: causes and regional impacts

Climate is broadly defined as the composite of long-term weather conditions including variations in temperature, precipitation, pressure and humidity. Climate change signifies a shift in these established patterns resulting from both natural dynamics and human influence. Since the 1800s, human activities particularly the combustion of fossil fuels like coal, oil and natural gas have emerged as the primary drivers of climate change (Gyawali & Kharel, 2024). The impacts of this shift are evident in phenomena such as global warming, increasingly unpredictable weather, rapid melting of glaciers and the continuous rise in sea levels all of which underline the urgency of addressing global climate issues (Hussain et al., 2020).

The predominant cause of climate change is the emission of greenhouse gases (GHGs). Although these gases exist naturally in the atmosphere their elevated concentrations significantly amplify the greenhouse effect and contribute to global climate alterations (Kipkemboi et al., 2021). Both natural systems and anthropogenic activities contribute significantly to greenhouse gas emissions. Natural sources encompass phenomena like forest fires, volcanic eruptions, mud volcanoes, wetlands, oceanic and seismic activity. On the other hand, human-related emissions are largely tied to energy production, industrialization and alterations in land use and forestry practices (Roy et al., 2022).

As defined by the Kyoto Protocol major greenhouse gases include CO₂, CH₄, N₂O and fluorinated gases such as HFCs, PFCs, and SF₆. The UNEP Emissions Gap Report (2019) stated that global GHG emissions in 2018 totaled was 55.3 GtCO₂e with 37.5 GtCO₂ originating from fossil fuel combustion and industrial processes. Anthropogenic influences have led to an estimated 1.0 °C increase in global temperatures above pre-industrial levels. If present emission levels persist warming is expected to reach 1.5 °C between 2030 and 2052 (Fawzy et al., 2020).

Climate change is projected to be the most critical global challenge in the decades ahead. In response UN Secretary-General António Guterres on December 13, 2020 called for a global State of Climate Emergency to remain in effect until carbon neutrality is attained. The formation of the Intergovernmental Panel on Climate Change (IPCC) in 1988 marked a pivotal moment of international consensus, aimed at equipping policymakers with scientific evidence to guide climate-related decision-making (Ouyang et al., 2022).

The impacts of climate change manifest globally; however, developing countries tend to

experience more severe consequence. This heightened vulnerability is attributed to several factors including limited public awareness, inadequate institutional capacity, inefficient resource management and generally weak economic conditions (Giri et al., 2021).

Over the past century, climatic events like El Niño and La Niña have reshaped global water and ecological systems. From 1895 to 1995, the Earth's temperature rose by nearly 0.4 °C triggering more frequent heatwaves and higher temperatures overall (Lopez et al., 2022). These changes are deeply felt in Pakistan where climate change manifests through reduced hydrological reserves, accelerated glacier loss and frequent extreme events such as floods and drought (Mahmood & Hassan, 2022). Forecasts indicate that the national temperature could rise by up to 1.5 °C by 2050. Historical climate disasters, including the 1998 and 2004 droughts, had devastating impacts, particularly in Balochistan, affecting a majority of the population and killed 76% of its livestock (Fahad & Wang, 2020). Additionally, recurring floods have displaced communities across large areas of the country, reinforcing Pakistan's status as climate-vulnerable..

Mountain areas face increasing risks from climate change with forecasts indicating intensifying environmental stress in the future. Local farmers reported a noticeable rise in temperatures along with unpredictable rainfall patterns both of which are threatening the long-term viability of livelihoods in these elevated regions (Adhikari et al., 2021).

2.2 Heat waves under climate change

In recent decades, climate change has substantially intensified global heatwaves with older populations particularly affected. From 2000 to 2021 heat-related deaths among individuals over 65 years increased by 68% highlighting a growing public health concern (Romanello et al., 2022). Heat stress refers to temperatures that exceed a critical limit. Extreme heat stress is determined by how high the temperature rises, how long it lasts and how quickly it increases (Farhad et al., 2023). In recent years heatwave drawn significant concern due to their widespread effects on human health, ecosystems, agriculture and the economy. With rising global temperatures heatwaves are becoming more intense, prolonged and frequent (Khan et al., 2021). Several recent heatwaves have led to significant mortality. The 2003 European heatwave caused approximately 70,000 deaths, while the 2010 heatwave in Eastern Europe resulted in 55,000 fatalities in Russia. In 2015 a heatwave in India claimed around 2,500 lives (Ullah et al., 2024).

Developing nations are particularly vulnerable to the effects of heat waves largely due to

insufficient infrastructure and limited adaptive capacity. This is especially evident in South Asia, where the frequency and intensity of heat waves, urban heat island effects, and heat stress are projected to increase. By the end of the century an estimated 185 to 492 million people in South Asia may be exposed to daytime heat waves, while 204 to 555 million could experience night time heatwaves (Ullah et al., 2022).

2.3 Impact of heat stress on livestock and agricultural sustainability

According to recent UN projections (2024), the global population is expected to reach approximately 9.7 billion by 2050. While agriculture remains crucial for livelihoods, particularly in developing regions, its global economic share has declined to about 4% of world GDP, employing around 27% of the global workforce (World Bank, 2023). Nonetheless, the sector faces increasing demands to feed a growing population.

The consumption of animal products alone is predicted to double by mid-century. This growing demand puts immense pressure on food systems to strike a sustainable balance between productivity, animal welfare, and environmental impact (Molotoks et al., 2021). Heat stress in domesticated livestock occurs when environmental factors overwhelm the animal's ability to regulate its body temperature. Such stress is typically caused by a combination of high temperatures, humidity, solar radiation and low wind speed that exceed the animal's thermoregulatory capacity (Thornton et al., 2021).

Climatic effects on cattle are assessed using environmental factors, animal traits or both. Key environmental variables include temperature, humidity, solar radiation, wind and precipitation. Due to data limitations many studies rely on simplified indices like the Temperature-Humidity Index (THI) which combines temperature and humidity into a single value. However, such indices may not fully reflect the complexity of heat stress or individual animal differences dairy cow (Gauly & Ammer, 2020).

Animals constantly gather and interpret both external and internal signals to regulate homeostatic functions. While these regulatory mechanisms differ both within and across species maintaining a stable internal environment remains critical for optimal growth and productivity (Martel et al., 2021). However, high temperatures, humidity or their combined effect measured as the Temperature-Humidity Index (THI) along with solar radiation and heat waves can disrupt these regulatory process.

When animals are unable to dissipate excess metabolic heat through conduction,

convection, radiation or evaporative cooling they enter a state of heat stress (Umar et al., 2021).

2.4 Heat stress in dairy cattle

Under high ambient temperatures or elevated Temperature-Humidity Index (THI), maintenance energy demands can rise by an additional 20%, increasing susceptibility to heat stress. Compared to non-lactating ("dry") cows, lactating Holstein Friesians regardless of milk yield level produce substantially more heat, with increases of 27% in low producers and 48% in high producers. This difference highlights how lactation intensifies thermal stress, making effective heat dissipation critical for maintaining performance and welfare (Idris et al., 2021). Moreover, studies show that hot weather affects cows' milk production and feed intake with a two-day delay, particularly when the Temperature-Humidity Index (THI) ranges from 72.1 to 83 (Mbuthia et al., 2021). Moreover, studies show that hot weather affects cows' milk production and feed intake with a two-day delay, particularly when the Temperature-Humidity Index (THI) ranges from 72.1 to 83 (Freeman, 2021). When cows cannot adequately dissipate heat, their body temperature rises, milk yield drops, fertility declines and in severe cases heat stress may cause death (Idrissou et al., 2020).

Physiological indicators such as respiration rate, heart rate and rectal temperature are commonly used to assess heat stress in cattle. However, these methods require intensive, continuous monitoring at the individual animal level which is often impractical. To address this the temperature-humidity index (THI) serves as a more accessible, noninvasive alternative that estimates heat stress levels using common weather data like temperature and relative humidity (Amponsah et al., 2020).

Furthermore, study highlighted that as temperatures and humidity levels surpass a cow's thermoneutral zone, heat stress (HS) poses significant economic risks for dairy producers. Genetic strategies for heat tolerance must be tailored to the production system where incorporating heat tolerance into breeding programs of high-productivity breeds is more beneficial for systems that can provide adequate resources to sustain animal productivity while crossbreeding with local breeds is more effective in resource-poor, harsh environments (Amamou et al., 2022).

2.5 Heat stress thresholds and their effects on milk yield and composition

Cows subjected to mild heat stress (THI 72-79) exhibit minimal effects on milk production primarily adapting by seeking shade increasing respiratory rate and vasodilation.

In contrast, at moderate heat stress levels (THI 80-89), there is a notable decline in milk yield and quality along with reduced reproductive efficiency, as cows experience elevated respiration, saliva production, water intake, body temperature and decreased feed consumption (Habimana et al., 2024). Some studies found that milk production declined when the THI surpassed 62, whereas some reported mild heat stress in cows at a THI greater than 68. This discrepancy in the critical THI thresholds for milk production can be explained by various factors, such as regional climate, the presence of cooling systems and genetic enhancements all of which influence the impact of THI on milk yield. THI levels above 98 can lead to cow mortality (Jeon et al., 2023). Effective heat stress management in dairy cows is essential when THI exceeds a critical threshold. This can be achieved by optimizing feeding practices and implementing a well-designed cooling system on the farm.

Further research has shown that climate change may profoundly affect the microbial content of raw milk, both directly through seasonal changes in temperature, humidity, rainfall, and sunlight and indirectly through cow heat stress. Direct effects include an increase in pathogenic and spoilage microbes in milk due to warmer, wetter, or sunnier conditions. Indirectly, elevated THI compromises cow health by weakening immune defenses, altering udder micro biota and promoting infections such as mastitis, which in turn reduces milk yield and alters its physical and chemical properties further impacting microbial profiles. These combined effects may reduce milk's safety, quality, and shelf-life, underscoring a need for targeted research and mitigation efforts (Feliciano et al., 2020).

The study emphasizes that dairy cows show noticeable declines in milk production once certain THI thresholds are crossed. Specifically, milk yield decreases when THI exceeds 82.25, while fat and protein corrected milk (FPCM) begins to fall at 80.24. Other important breakpoints include 79.83 for fat yield, 79.43 for protein yield, and 78.00 for the fat-to-protein ratio. A THI of 80.23 marks the limit for solids-not-fat (SNF), and lactation persistency significantly drops beyond a THI of 77.87. These findings point to the sensitivity of dairy cows to heat stress and highlight how increased THI can compromise both productivity and milk quality. (Forget et al., 2021). Under heat stress conditions, dairy cows activate various physiological and behavioral strategies to manage excess body heat. One frequently observed adaptation is the down regulation of metabolic processes to reduce endogenous heat production. However, this often leads to a decline in feed intake, ultimately contributing to decreased milk production (Chen et al., 2024). Changes in cows 'metabolic functions and physiological state are often reflected in variations in milk composition.

Physiological state are often reflected in variations in milk composition. Studies consistently report that heat stress adversely affects milk quality in dairy cattle, leading to lower protein and casein concentrations, reduced milk fat, and shifts in fat composition toward longer fatty acid chains changes that may impair both nutritional value and processing properties of dairy products (Cheng et al., 2022).

Climate change is linked to a range of negative impacts on livestock production, largely due to the rising frequency of extreme weather events such as heatwaves, extended warm spells, and intense phenomena like floods and hail. These events have been shown to impair animal health, welfare, reproductive efficiency, and overall physiological balance. Moreover, studies show that the dairy sector is particularly at risk, as heat stress not only lowers milk yield but also alters its composition. These changes ultimately compromise the quality and quantity of dairy products, affecting the entire value chain (Yan et al., 2021).

2.6 Climate change and livestock-dependent livelihoods

Livestock contribute significantly to human well-being by providing essential products and services. Globally, they utilize approximately 26% of ice-free land, while nearly one-third of all croplands are dedicated to producing animal feed. The sector also offers critical employment opportunities particularly within rural communities. In developing nations, livestock are vital sources of food, nutritional security, livelihoods and household income (Cheng et al., 2022).

According to a recent study by the Food and Agriculture Organization of the United Nations (2023), climate change is expected to severely affect livestock systems particularly cattle and buffaloes which are critical sources of meat and milk. Under projected climate change conditions increasing heat stress is anticipated to decrease meat production by up to 22% and milk output by approximately 21% by the year 2085 creating substantial challenges for food security and populations reliant on livestock for sustenance and income (Bobe et al., 2021).

Current studies reveal that climate-induced pressures particularly rising temperatures and severe weather fluctuations are increasingly diminishing livestock output thereby destabilizing rural livelihoods. Stakeholders including farmers recognize the threat of these changes pose to food systems and household incomes. In response, scholars stress the need for proactive policy interventions and climate-resilient agricultural practices. These measures are essential not only to protect the productivity of the livestock sector but also to strengthen the socio-economic resilience of rural communities in the face of ongoing climate challenges (Singh et al., 2024).

2.7 Global dairy production under climate stress

Globally, more than 844 million people rely on agriculture for their livelihoods with the livestock sector contributing around 40% to the value added in agriculture (Wagoner et al., 2020). Climate change is anticipated to influence the role of livestock in food security and broader sustainability goals though the exact extent and severity of these impacts are still not fully understood.

Because of its prevalence across various regions heat stress is likely one of the most extensively studied issues in the global dairy industry increasingly drawing the attention of both researchers and farmer (Herbut et al., 2020). While heat stress can occur in all climate zones depending on the season. However cows in tropical, subtropical and Mediterranean areas endure longer heat exposure and recover more slowly than those in temperate zones. The humid subtropical climate of the southeastern U.S., marked by high heat and humidity, restricts heat loss through evaporation.

The growing concern regarding the thermal comfort of dairy cows is not limited to tropical regions but extends to temperate zones, where rising temperatures are becoming a significant issue. Recent studies in temperate countries such as Germany and United States of America (USA) have highlighted heat stress as a key factor adversely affecting milk production, reproduction and overall cow health (Ranjitkar et al., 2020). A study in Italy predicts a 2.1% decline in dairy farmers' net income by 2030 due to climate-related factors, while Irish research forecasts annual losses of 1 to 2 billion euros by mid-century. Both major and smaller dairy-producing Europe countries, including those in the Mediterranean, are expected to face significant economic challenges in dairy production and export as a result of climate change. These findings emphasize the substantial financial risks climate change poses to the European dairy industry (Wankar et al., 2021).

The influence of climate change on dairy production varies by region, with some areas experiencing beneficial effects like improved pasture growth due to increased rainfall, while others suffer from adverse conditions such as drought and heatwaves. These region-specific effects require targeted adaptation strategies, including water management and infrastructure modifications. Moreover, the sector's response is influenced by economic factors and policy support for sustainable practices. Additionally, the dairy industry plays a dual role as both a contributor to climate change through methane and nitrous oxide emissions and a potential

mitigator through sustainable land-use practices that promote carbon storage (Neethirajan, 2024).

2.8 Livestock vulnerability in developing nations

Growing demand for livestock products in low- and middle-income nations alongside rising temperatures creates a difficult situation. Meeting both adaptation and productivity goals may require considerable infrastructural investment (Thornton et al., 2022). Recent studies highlight that the livestock sector in developing countries particularly in West Africa where it contributes to over one-third to the agricultural GDP, is highly vulnerable to climate change. Fluctuations in temperature and humidity beyond optimal levels impose physiological stress on animals leading to reduced productivity, compromised performance and increased mortality. Heat exposure at 32 °C can suppress forage intake by 18% and reduce milk output by 32%, relative to more favorable conditions at 16 °C (Rahimi et al., 2020).

In Saharan regions, native Holstein cows experience a decline in milking performance, particularly during summer when the temperature-humidity index (THI) exceeds 80. However, native Holsteins demonstrate greater resistance to hyperthermia compared to imported breeds (Ouarfli & Chehma, 2021). The Temperature-Humidity Index (THI), a combined measure of temperature and relative humidity, is widely utilized in heat stress research. A substantial body of literature has identified significant risks to production efficiency and animal welfare during periods of elevated THI (Niyonzima et al., 2022).

Moreover studies conducted in eight key milk-producing provinces of China have shown that elevated summer temperatures are strongly associated with decreased milk yields in dairy cattle leading to financial losses within the dairy sector. Additionally, heat stress impairs milk quality by lowering protein levels, which are essential for its nutritional integrity (Mendonca et al., 2025).

Dairy farming is increasingly affected by heat stress, which harms both milk production and financial returns. Hot weather leads to recurring drops in milk yield and changes in quality. Over the years, breeding cows for more milk may have made them less able to cope with heat, since they naturally generate more body heat. With climate change likely to make these conditions worse researchers and producers are focusing more on modeling and measuring how heat stress affects dairy performance (Mbuthia et al., 2021).

Recent studies indicate that climate change will disproportionately impact the livestock sector in developing countries. In West Africa ,w here livestock contributes significantly over

one-third to the agricultural GDP, the sector remains economically vital.

However, despite this significance and the region's high vulnerability to climate change, limited research exists on how shifting climate patterns may influence livestock heat stress in the area (Kom et al., 2022). The understanding of farm-level vulnerability and adaptation processes remains inadequate, particularly in developing countries, due to insufficient research on environmental stressors and the underlying mechanisms of adaptation. Rising heatwaves, exacerbated by climate change are severely impacting livestock productivity in North India threatening the economic stability of the dairy farming sector. The unprecedented temperatures of the 2022 summer particularly in March and April highlight the increasing vulnerability of livestock systems to climate-induced stress potentially resulting in significant production losses (Park et al., 2022).

Heat stress significantly threatens agricultural productivity, especially in both crop and livestock sectors. To manage its effects, strategies such as modifying the surrounding environment, improving dietary inputs, and developing heat-tolerant livestock breeds are essential. These measures, whether implemented independently or in combination, provide viable approaches to enhancing resilience in high-temperature conditions (Thiery et al., 2020).

2.9 South Asia's livestock sector in a changing climate

The increasing frequency of extreme weather events highlights climate change as a serious global issue with far-reaching consequences. Several studies have highlighted that the primary vulnerability to climate change in South Asia stems from the region's heavy reliance on a rural agriculture-based economy which supports a large and growing population. This dependence places considerable stress on social systems, economic stability and ecological balance. Furthermore, the region's geographical limitations, scarcity of resources, and high dependence on climate-sensitive livelihoods leave the poorest communities particularly susceptible to the adverse impacts of climate change (Sharma & Andhikaputra, 2022). Livestock productivity faces serious limitations during the summer months, especially in tropical and subtropical climates where animals are highly susceptible to heat stress. South Asia, which falls within these climatic zones, regularly experiences summer temperatures exceeding 45°C around 18°C above the thermal tolerance limit for dairy cattle. As a result, heat stress emerges as a key barrier to optimal livestock performance in this region (Akbar et al., 2021).

Furthermore research indicates that climate change has adversely affected Bangladesh's

livestock sector by increasing disease prevalence, intensifying heat stress and reducing productivity due to elevated temperatures and erratic rainfall.

These factors compromise animal health and farm profitability. Addressing these impacts necessitates improved husbandry practices, the introduction of climate-resilient breeds, and alternative feeding strategies (Dey, 2023).

Fluctuating climatic conditions and extreme weather events have negatively influenced both the quality and quantity of livestock outputs including milk, wool, and meat leading to reduced market prices and unstable production patterns. These disruptions pose significant risks to food security. Addressing the complex challenges arising from climate change such as livestock health issues, shortages in feed supply, and unpredictable milk pricing has become increasingly difficult due to the scarcity of localized climate data and forecasting systems.

An anticipated 2 °C rise in average global temperatures by 2050 is expected to increase health-related challenges in livestock, as heat stress can suppress immune function and lead to a higher likelihood of infectious disease outbreaks (Montcho et al., 2022). Therefore, there is a pressing need for location-specific decision-support frameworks to help smallholder dairy farmers effectively respond to climate-induced risks (Thornton et al., 2022).

2.10 Pakistan's dairy Sector

In developing and semi-arid regions such as Pakistan's agriculture serves as the backbone of the economy supporting nearly 50% of the workforce. Pakistan ranks among the most heatwave-prone countries, with temperatures often surpassing 50 °C between May and September (Rana et al., 2022). Several studies in Pakistan have highlighted the vulnerability of milking animals and specific agricultural crops to heat stress and rising temperatures. For example, an increase in temperature has been shown to reduce milk production by 10–20% (Abbas et al., 2024). In Punjab province numerous studies have addressed climate change adaptation in dairy farming. For example research conducted in Central Punjab reveals that livestock farmers have adopted traditional climate change strategies, such as mixed farming, reducing livestock numbers, increasing the provision of drinking water, utilizing tree shades, employing mud roofs and floors to mitigate climate impacts. The adoption of these strategies was significantly influenced by factors such as animal inventory, climate change knowledge, livestock working hours, livestock experience, proximity to veterinary services and participation in livestock-related workshops (Mehmood et al., 2022). Despite a vast livestock population, Pakistan's dairy sector lags

internationally largely due to climate-induced losses in production.

A variety of factors such as diminished animal growth, decreased milk yield and reproductive efficiency declines in feed quality and quantity, increased disease burden and water scarcity heat stress and disrupted animal behavior are closely linked to changing temperature and precipitation patterns. Since the mid-20th century, Pakistan has witnessed rising temperatures, more frequent heatwaves, erratic rainfall and declining per-capita income. This climate variability has had a disproportionately adverse effect on cattle and buffalo, which are highly heat sensitive (Shahbaz et al., 2020).

Although numerous studies have addressed climate change adaptation in dairy farming across various districts of Punjab. Currently, there is a significant gap in data regarding the quantification of heat stress (HS) impacts and their economic consequences which constrains the capacity of dairy farms in Punjab to make evidence-based decisions on heat stress management under future climate change scenarios. This lack of information impedes the formulation of effective strategies for mitigating heat stress in the region. However, this gap in the existing literature persists, as Chakwal a critical hub for livestock production has been excluded from previous analyses. Given its semi-arid climate and susceptibility to heatwaves, understanding local THI thresholds and their impact on milk yield and quality is essential. The current study will bridge these gaps by concentrating on Chakwal, providing a detailed analysis of the effects of heat stress on dairy productivity and offering insights into climate adaptation strategies specific to this region.

CHAPTER 3

MATERIALS AND METHODS

Chapter 3

3. Materials and Methods

3.1 Study Area

This study was conducted in the Chakwal District of Punjab, Pakistan. Geographically, Chakwal is situated at 32° 55' 29.39" N latitude and 72° 51' 11.99" E longitude, with an elevation of 498 meters above sea level. The district features a semi-arid, subtropical climate characterized by hot summers where temperatures frequently peak at 45°C in June and July, and annual rainfall is low and erratic, averaging 133 mm. These specific climatic conditions make Chakwal a critically relevant site for investigating heat stress in dairy cattle. The combination of high summer temperatures and the district's location as a rain-fed agricultural region heightens its vulnerability to climate variability. With over 80% of its population residing in rural areas and heavily dependent on agriculture and livestock, the economic impact of heat stress on dairy productivity is a pressing concern. The presence of both traditional and modern dairy farms in the district, holding over 290,000 cows, provides a viable context for assessing the impacts of climate-induced heat stress, thereby addressing a significant gap in the regional literature. Figure 3.1 showing the study area map.

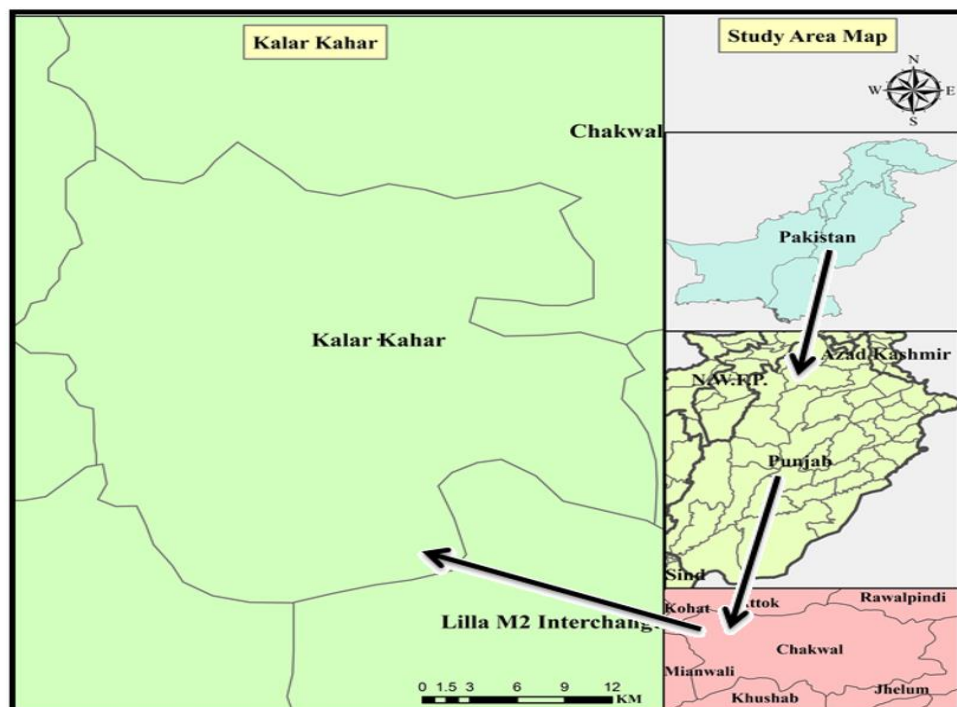


Figure 3.1: Study area map showing the geographical location of Chakwal (Kallar Kahar), Pakistan.

3.2 Experimental Farm Characteristic

3.2.1 Farm Selection and Characteristics

This study was conducted at the Daim dairy farm in Tehsil Kallar Kahar, Chakwal, which was selected purposively due to its advanced management practices, high-yielding herd of Dutch-origin Holstein Friesian cows, and comprehensive digital record-keeping system; these features were essential for ensuring data accuracy, consistency, and the ability to monitor individual animal performance over time. The farm maintains a herd of approximately 450-500 cattle in well-ventilated, semi-open housing. The research was conducted using the farm's existing cooling infrastructure which was comprised of axial fans, overhead sprinklers, and a pilot program of rooftop insulation on one shed which collectively established a controlled microclimate with measurable environmental variation. Furthermore, the availability of detailed digital records for each animal including date of birth, calving history, parity, days in milk, and health status was crucial for the precise selection of the experimental cohort and for controlling confounding variable.

3.2.2 Animal Selection Criteria

A sample of 50 lactating Holstein Friesian cows was selected based on strict criteria to ensure herd uniformity and limit the influence of non-climatic factors. The selected animals were 3 to 7 years old, in their 1st to 5th lactation, and between 1 to 6 months in milk to target the peak production phase. All cows were clinically healthy at the study's onset, with no signs of mastitis or metabolic disease. Any animals that developed health issues during the study were excluded from the final analysis.

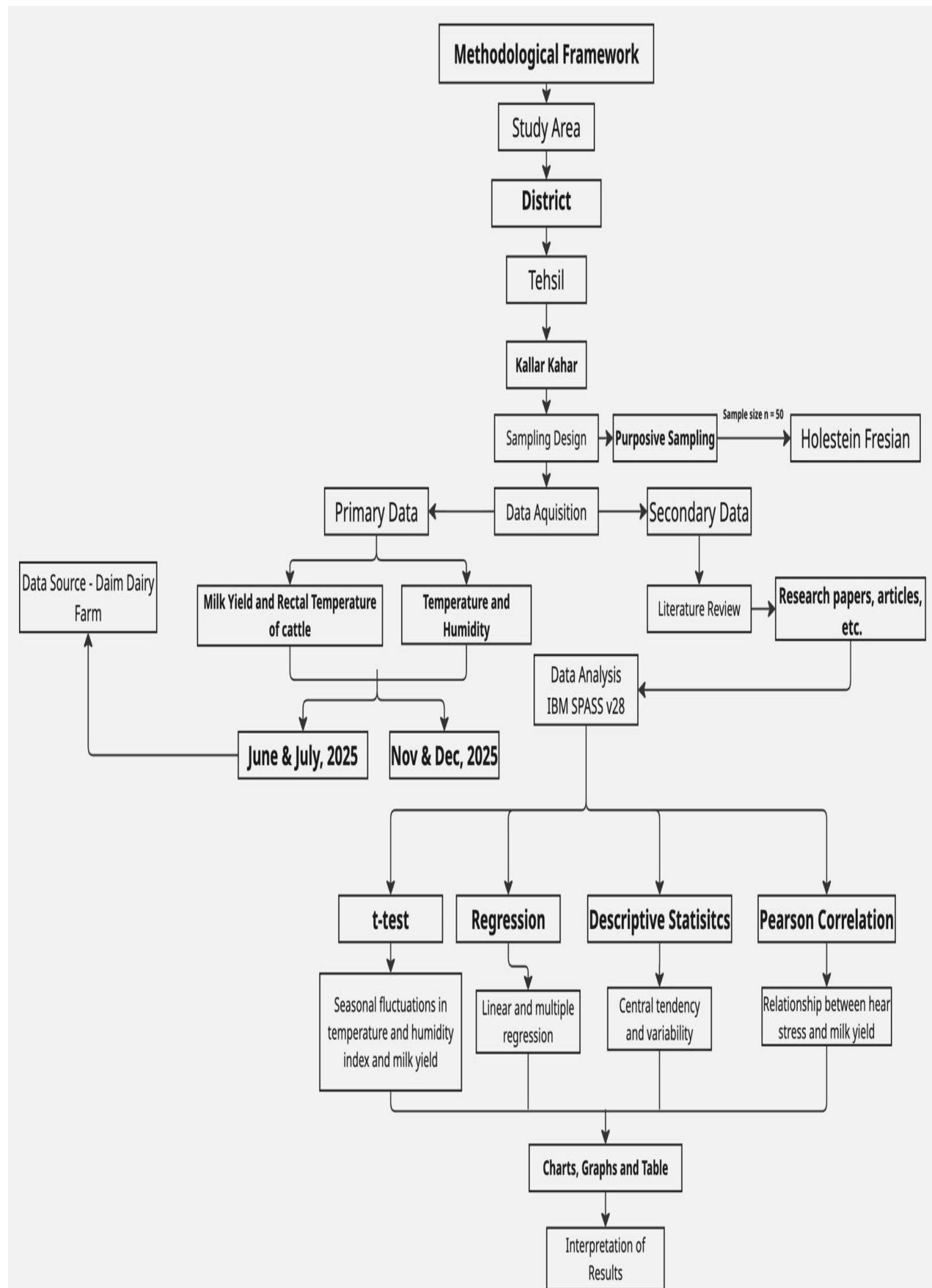
3.3 Experimental Design

A single-cohort, observational study design was employed to monitor the same group of 50 cows across in two distinct climatic seasons in 2025. The high heat-stress period (Summer, June–July) and the low heat-stress period (Winter, November–December). This within-subject design allowed for a direct comparison of each animal's performance under different environmental conditions thereby increasing the statistical power to detect heat stress effects. The primary dependent variables were milk yield (kg/day) and milk composition (fat, lactose, and SNF percentages), while the key independent variable was heat stress quantified using the Temperature-Humidity Index (THI). All animals were managed under the farm's standard operating procedures including a consistent Total Mixed Ration (TMR) diet (Table 3.1) and free

access to clean drinking water, to control for nutritional variability.

Table 3.1: Feed ingredients and chemical composition of the concentrated diet.

Major Feed Ingredients	Quantity per Cow (kg)	Nutritional Supplements	Quantity per Cow (g)
Corn Silage	33.00	Premix Mineral	0.12
Rhode Grass	2.50	Dicalcium Phosphate (DCP)	0.09
Hay			
Yellow Corn	5.00	Live Yeast	0.09
Soybean Meal	3.00	Toxin Binder (Y)	0.01
Canola Meal	3.00	Toxin Binder (C)	0.03
Wheat Bran	1.50	Soda Bicarbonate	0.15
Molasses	1.50	Insta Energy	0.19
Methionine	0.01	Magnesium Oxide	0.06
Total	50.50 kg		



3.4 Data Acquisition

A systematic data collection protocol was implemented across two distinct seasonal periods: summer (June and July) and winter (November and December) 2025 drawing from three primary sources: environmental monitoring, farm production records and direct physiological measurements. Environmental conditions and milk yield data were recorded daily, while milk composition and physiological parameters were aggregated into weekly composites. This approach was designed to harmonize the datasets and mitigate the impact of daily variations, thereby providing a robust analysis of seasonal trends.

3.4.1 Environmental Data

Primary environmental data consisting of maximum and minimum air temperature (°C) and relative humidity (%) were collected using electronic meters installed inside and outside the dairy shed at the Daim dairy farm. This directly sourced data was used to calculate the Temperature-Humidity Index (THI) to evaluate heat stress. The established formula for Daily Maximum THI ($THI_{max} = (1.8 \times T_{max} + 32) - [(0.55 - 0.0055 \times RH) \times (1.8 \times T_{max} - 26.8)]$) was applied where T_{max} is the maximum dry-bulb temperature and RH is the relative humidity. This calculation provided a precise gauge of the peak heat stress conditions experienced by the animals each day.

3.4.2 Milk Production and Composition Data

Milk yield data was collected as primary data, with the daily production in liters for each individual cow in the cohort being automatically recorded and summed from three milking sessions by the farm's regularly calibrated mechanical milking system. For milk composition—specifically fat, lactose, and Solids-Not-Fat (SNF) percentages—secondary data were obtained from quality reports generated by the dairy processing company that purchased milk from the farm, which used standardized automated milk analyzers; although reported daily by the company, this compositional data was aggregated to a weekly basis for analysis to align with physiological data and mitigate the impact of daily variations.

3.4.3 Physiological Data

As a direct indicator of core body temperature and heat stress, rectal temperature was measured once per week for each cow in the cohort using a calibrated digital clinical thermometer,

with all measurements taken in the morning prior to the first milking session to ensure consistency and minimize diurnal variation.

Additionally, environmental parameters such as temperature and humidity, was monitored. The Temperature-Humidity Index ($THI_{max} = (1.8 \times T_{max} + 32) - [(0.55 - 0.0055 \times RH) \times (1.8 \times T_{max} - 26.8)]$) was employed to quantify heat stress, combining air temperature and relative humidity into a single value. A higher THI was indicating more intense heat stress, offering valuable insights into its impact on milk yield and cow health.

THI Formula

$$THI_{max} = (1.8 \times T_{max} + 32) - [(0.55 - 0.0055 \times RH) \times (1.8 \times T_{max} - 26.8)] \quad (1)$$

Where T_{max} represents the daily maximum air temperature ($^{\circ}C$) and RH indicates the relative humidity (%) for the given day.

3.5 Statistical Analysis

All statistical analyses were performed using IBM SPSS Statistics Version 28 with a significance level (α) set at 0.05 for all tests. The analytical approach was designed to comprehensively address the study's objectives, beginning with descriptive statistics to summarize all environmental, production and physiological variables.

3.5.1 Descriptive Statistic

Descriptive statistics was used to summarize the central tendencies and variability of the data. Key weather variables, including temperature, humidity and the Temperature Humidity Index (THI) as well as milk yield was analyzed. The mean (M) and standard deviation (SD) was calculated for each of these variables to provide a comprehensive overview of their distribution and variability across the study period.

3.5.2 Correlation Analysis

To investigate the relationship between climatic factors (such as THI, temperature and humidity) and milk yield, Pearson's correlation coefficient (r) was computed. This analysis was assessed the strength and direction of the associations between heat stress quantified by THI and dairy productivity. A significant correlation revealed the extent to which changes in environmental conditions were related to fluctuations in milk yield with the sign of the coefficient indicating whether the relationship is positive or negative. Correlation analysis was also used for qualitative analysis.

$$r = \frac{\sum (xi - \bar{x})(yi - \bar{y})}{\sqrt{\sum (xi - \bar{x})^2 \sum (yi - \bar{y})^2}} \quad (2)$$

- . xi and yi individual data point
- . $\bar{x}$ and $\bar{y}$ sample mean of X and Y
- . n is number of data pair

3.5.3 T-test for Seasonal Comparison

An unpaired t-test was performed to compare the mean values of milk yield and THI between the two seasonal conditions: summer and winter. This parametric test was determined if there were statistically significant differences in milk yield and heat stressed levels across the seasons. Specifically, the test compared reduced milk yields during the summer when heat stress was typically higher against potentially higher yields in the winter months when environmental stress was minimal.



(3)

- . $\bar{x}_1$ and $\bar{x}_2$ are mean of first and second group
- . S is the pool standard deviation of first and second group
- . n is sample size of group

3.5.4 Regression Analyses

Regression analyses were central to modeling the predictive relationships between variables; specifically, Simple Linear Regression was utilized to quantify the influence of individual factors like humidity on milk yield and composition, while Multiple Linear Regression was employed to model the combined effect of temperature and humidity on milk yield, thereby controlling for the collinearity between these two factors.

CHAPTER 4

RESULTS

Chapter 4

4. Results

This study was designed to assess the impacts of heat stress on milk production and composition in lactating Holstein Friesian dairy cows, while also evaluating seasonal variations in environmental parameters and their effects on productivity. The research employed both primary data and secondary data collection of environmental conditions, physiological parameters and milk production metrics with advanced statistical analysis. All analyses were conducted using IBM SPSS Statistics Version 23 proceeding through sequential phases of descriptive statistics, correlation analysis regression modeling and mediation analysis with statistical significance set at $p < 0.05$ after verifying assumptions of normality and linearity.

4.1 Characterization of Environmental Conditions

The data presented in table 4.1 confirm that the dairy cows were subjected to a persistent heat stress environment, with the mean Temperature-Humidity Index (THI) inside the shed (81.13 ± 3.16) consistently exceeding the critical threshold of 72. Although the external THI was marginally higher (83.58 ± 3.91), the shelter's performance revealed a critical trade-off. It was effective at significantly reducing peak temperatures, as shown by the lower mean and reduced range of internal temperature (33.32 ± 4.04 °C) compared to the external environment (36.73 ± 5.00 °C). This moderation of external extremes is further supported by the negative skewness of the outside temperature (-0.66), which indicates a left-tailed distribution with more frequent cooler extremes, whereas the near-zero skewness inside (0.10) suggests a more uniform and stable thermal environment. However, the shed inadvertently exacerbated the humidity, creating a more humid microclimate ($44.15 \pm 20.53\%$) compared to outside ($39.82 \pm 18.75\%$). The positive skewness for humidity both inside (0.32) and outside (0.90) indicates that periods of very high humidity occurred, with the stronger positive skewness outside suggesting that the external environment was more prone to extreme humid events. The kurtosis values provide additional insight into the distribution shapes. The negative kurtosis for internal humidity (-1.02) denotes a platykurtic flat distribution with lighter tails implying less frequent extreme humidity spikes inside than would be expected in a normal distribution. In contrast, the positive kurtosis for external

humidity (0.89) signifies a leptokurtic peaked distribution where data are concentrated around the mean but with a higher propensity for extreme outliers. Ultimately, while the shed successfully moderated temperature extremes the resulting humid microclimate directly impaired the cows' primary method of evaporative cooling through panting thereby likely exacerbating their physiological heat stress despite the provision of shade.

Table 4.1: Characterization of environmental conditions

Parameter	Location	N	Mean $\pm$ SD	Range	Skewness	Kurtosis
Temperature Humidity Index	Inside	62	81.13 $\pm$ 3.16	74-87	-0.66	-0.16
	Outside	62	83.58 $\pm$ 3.91	72-90	-0.97	1.37
Temperature (°C)	Inside	62	33.32 $\pm$ 4.04	24-43	0.10	-0.21
	Outside	62	36.73 $\pm$ 5.00	23-46	-0.66	0.54
Humidity (%)	Inside	62	44.15 $\pm$ 20.53	18-87	0.32	-1.02
	Outside	62	39.82 $\pm$ 18.75	17-99	0.90	0.89

4.2 Milk Yield Patterns and Distribution

Based on the analysis of milk production data presented in table 4.2, the herd's output was variable with a total daily yield averaging $1,740.19 \pm 110.28$ liters and a considerable range from 1,558 to 1,923 liters. This variability is further reflected in the average yield per day which was 68.31 ± 4.34 liters per day ranging from 61 to 75 liters. The distribution patterns for both total and average yield are particularly revealing. The near-zero positive skewness values (0.21 and 0.17, respectively) indicate a relatively symmetrical distribution where extremely low and high production days were equally uncommon, with a very slight tendency towards the higher end of the range. More significantly, the distinct negative kurtosis values (-1.26 and -1.30) confirm a platykurtic distribution, meaning the data are flatter and more widely dispersed than a normal bell curve. This pattern is critical as it demonstrates that daily yields were not consistently clustered around the mean but were instead influenced by multiple fluctuating factors beyond the persistent heat stress.

Table 4.2: Milk yield patterns and distribution.

Variable	N	Mean $\pm$ SD	Range (Min-Max)	Skewness	Kurtosis
Total Milk Yield (liters/day)	62	1740.19 $\pm$ 110.28	1558 – 1923	0.21	-1.26
Average Milk Yield (liters/cow/day)	62	68.31 $\pm$ 4.34	61 – 75	0.17	-1.30

4.3 Weekly Heat Stress and Production Trends

The analysis of weekly data presented in Table 4.3 indicates that over the eight-week period the herd experienced a sustained state of heat stress resulting in a range of adverse effects.

Table 4.3: Weekly heat stress and production trends.

Variable	Mean	Standard Deviation	Minimum	Maximum
Environmental Parameters				
THI Inside	80.56	1.55	78.1	82.6
Temperature Inside (°C)	33.75	2.73	30.6	37.4
Humidity Inside (%)	40.59	19.15	18.0	65.0
THI Outside	83.49	1.59	81.1	85.7
Production Metrics				
Total Milk Yield (Liters)	1768.25	122.28	1608.0	1923.0
Fat Content (%)	4.13	0.05	4.06	4.20
Lactose Content (%)	4.74	0.06	4.65	4.82
SNF Content (%)	8.78	0.03	8.73	8.82
Animal Physiology				
Rectal Temperature (°F)	102.89	0.11	102.70	103.02

The mean Temperature-Humidity Index (THI) inside the shed was 80.56, with a narrow weekly range from a minimum of 78.1 to a maximum of 82.6 confirming a persistent and critically high thermal load that consistently exceeded the established heat stress threshold of 72. This was driven by a combination of high internal temperatures (Mean: 33.75°C; Range: 30.6–37.4°C) and substantial weekly fluctuations in humidity (Mean: 40.59%; Range: 18.0–65.0%), a microclimate created by the shed's trade-off of reducing radiant heat at the cost of trapping moisture. The physiological toll of this environment is clearly demonstrated by the elevated and stable mean rectal temperature of 102.89°F with a minimal range from 102.70 to 103.02°F, indicating a state of persistent hyperthermia. Milk production while maintaining a respectable average total yield of 1768.25 liters per week exhibited considerable volatility (Range: 1608.0–1923.0 liters) indicating that the cows' metabolic systems were under intermittent strain. So the energy normally allocated for milk synthesis was diverted to thermoregulation leading to yield variability. However, the

remarkable stability in milk composition evidenced by the extremely narrow ranges in fat content (4.06–4.20%), lactose content (4.65–4.82%) and SNF content (8.73–8.82%) suggests that the herd's basal metabolic functions and ration quality were maintained, preserving milk quality even as quantitative output was compromised by the unrelenting heat stress.

Table 4.4: Dominant influence of humidity

Variable	THI Inside	Temperature Inside	Humidity Inside	Total Milk Yield	Average Milk Yield
THI Inside	1				
Temperature Inside	.69**	1			
Humidity Inside	-.12	-.77**	1		
Total Milk Yield	-.15	.49**	-.81**	1	
Average Milk Yield	-.08	.56**	-.83**	.98**	1

Note: Indicates significance at $p < 0.01$.

4.4 Dominant Influence of Humidity

The analysis shows that within this specific management system, the conventional Temperature-Humidity Index (THI) is an inadequate predictor of milk yield, as it exhibited no significant correlation with production outcomes, as demonstrated in Table 4.4. The primary reason for THI's lack of significance is that its formula assigns balanced weight to both temperature and humidity thereby obscuring the dominant and disproportionate physiological impact that humidity exerts on the cows' ability to dissipate heat. In contrast internal humidity alone revealed a powerful and significant negative correlation with milk yield ($r \approx -0.82$, $p < 0.01$). This is mechanistically justified because high humidity directly saturates the air, nullifying evaporative cooling through panting and forcing a metabolic shift away from milk synthesis toward survival-focused thermoregulation. The significant inverse correlation between internal temperature and humidity ($r = -0.77$, $p < 0.01$) further clarifies the microclimate indicating that the most thermally challenging periods (high THI) could be either hot-dry or warm-humid. It is the latter condition precisely captured by high humidity readings that proved most detrimental to productivity, explaining why the composite THI metric failed to correlate with yield while its individual humidity component emerged as the definitive environmental stressor.

The analysis revealed a significant positive correlation between internal temperature and milk yield ($r \approx 0.53$, $p < 0.01$). This relationship is not an indication that heat is beneficial, but rather a direct consequence of the strong negative correlation between temperature and humidity inside the shed ($r = -0.77$, $p < 0.01$). This inverse dynamic created periods where higher temperatures coincided with lower, less critical humidity levels. Consequently, these "hot-dry" conditions were less physiologically disruptive than "cool-humid" periods, as the drier air allowed the cows' primary evaporative cooling mechanism to remain partially effective.

4.5 External Environment and Milk Yield

Data from the external environment, detailed in table 4.5, demonstrate that the negative impact of high humidity on milk yield is not merely a consequence of housing design but a fundamental characteristic of the regional climate in Chakwal district posing a systemic challenge to dairy production. External humidity demonstrated a strong and significant negative correlation with both Total and Average Milk Yield ($r \approx -0.69$, $p < 0.01$). This result is critically significant as it confirms that the physiological impairment of evaporative cooling due to humid conditions is a pervasive environmental challenge. In contrast, the external Temperature-Humidity Index (THI) showed no significant relationship with production a finding justified by its failure as a composite metric to isolate humidity's dominant role. This is clarified by the opposing correlations of its components. External temperature exhibited a significant positive correlation with milk yield ($r \approx 0.40$, $p < 0.01$). This apparent paradox is resolved by the strong inverse relationship between external temperature and humidity ($r = -0.78$, $p < 0.01$), indicating that hotter days were consistently drier.

Table 4.5: External environment and milk yield.

Variable	THI Outside	Temperature Outside	Humidity Outside	Total Milk Yield	Average Milk Yield
THI Outside	1				
Temperature Outside	.79**	1			
Humidity Outside	-.35**	-.78**	1		
Total Milk Yield	.038	.41**	-.69**	1	
Average Milk Yield	-.004	.38**	-.68**	.98**	1

4.6 Shed vs. Outdoor Environment

The shelter's modification of natural conditions, as shown in Table 4.6 led to a consequential compromise in the microclimate, directly influencing the physiology of the herd. While significantly reducing the thermal load - evidenced by the lower mean THI inside (81.13 ± 3.16) versus outside (83.58 ± 3.91) with a substantial mean difference of -2.45 ($t[61] = -5.49$, $p < 0.001$, 95% CI $[-3.34, -1.56]$) - this benefit came at a critical cost. The temperature reduction from $36.73 \pm 5.00^{\circ}\text{C}$ outside to $33.32 \pm 4.04^{\circ}\text{C}$ inside (mean difference: -3.40°C , $t[61] = -6.85$, $p < 0.001$, 95% CI $[-4.40, -2.41]$) was counteracted by a significant humidity increase from $39.82 \pm 18.75\%$ outside to $44.15 \pm 20.53\%$ inside (mean difference: $+4.32\%$, $t[61] = 3.28$, $p = 0.002$, 95% CI $[1.69, 6.96]$). The strong t-values and narrow confidence intervals excluding zero confirm these are robust, reliable effects rather than chance occurrences. This humidity elevation directly impaired the cows' evaporative cooling capacity through panting mean the shelter's design ultimately exacerbated physiological heat stress despite providing thermal protection.

Table 4. 6: Paired samples comparison internal Vs. external environmental parameters

Parameter	Location	Mean $\pm$ SD	Mean Difference	t-value	p-value	95% CI of Difference
THI	Inside	81.13 ± 3.16	-2.45	-5.49	$<.001$	-3.34 to -1.56
	Outside	83.58 ± 3.91				
Temperature ($^{\circ}\text{C}$)	Inside	33.32 ± 4.04	-3.40	-6.85	$<.001$	-4.40 to -2.41
	Outside	36.73 ± 5.00				
Humidity (%)	Inside	44.15 ± 20.53	$+4.32$	3.28	$.002$	1.69 to 6.96
	Outside	39.82 ± 18.75				

4.7 Simple Linear Regression Analysis of Humidity on Milk Yield

Simple linear regression confirms internal shed humidity as a significant predictor of milk yield with a strong negative correlation ($R = 0.81$) explaining 66.5% of the variance ($R^2 = 0.66$, Fig. 4.1) as shown in Table 4.7.

Table 4.7: Simple linear regression analysis of humidity on milk yield.

Regression Statistics	Value
R	0.81
R ²	0.66
Adjusted R ²	0.66
Standard Error	64.31
F-statistic	119.33

p-value	<0.001			
Sample Size (N)	62			
Predictor	Coefficient	Std. Error	t-value	p-value
Constant	1933.61	19.49	99.16	<0.001
Humidity Inside Shed	-4.38	0.40	-10.92	<0.001

This critical value indicates that 66.5% of the total variance in daily milk output can be attributed directly to fluctuations in shed humidity, a finding further validated by the adjusted R^2 (0.66), which confirms the model's robustness. The overall significance of the regression model is unequivocally demonstrated by the F-statistic of 119.33 with a p-value of < 0.001 , confirming that the model fits the data significantly better than a model with no predictors. The regression equation, derived from the predictors, is: Milk Yield = $1933.61 - 4.38(\text{Humidity } \%)$. The constant (intercept) of 1933.61 ($p < 0.001$) represents the theoretical milk yield in liters at zero humidity, establishing the production potential under ideal conditions. The slope for 'Humidity Inside Shed' is -4.38, which is highly significant ($t = -10.924$, $p < 0.001$). This coefficient is the core finding of the model, as it quantifies that for every 1% increase in shed humidity, the total daily milk yield decreases by 4.38 liters, holding all other factors constant. The very small standard error (0.40) associated with this coefficient underscores the high precision of this estimate. This precise quantification provides a tangible economic metric, enabling direct financial forecasting and underscoring the urgent need for humidity-specific mitigation strategies in dairy management.

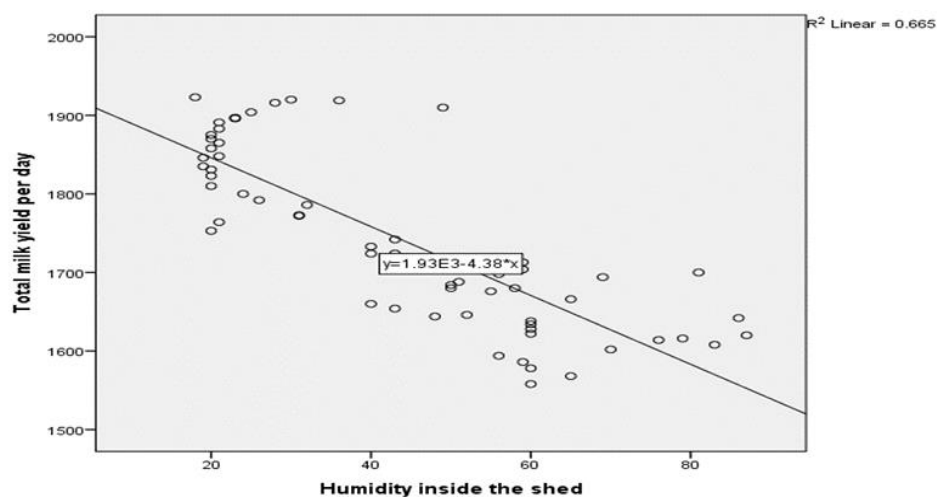


Figure 4.1: Linear relationship between internal shed humidity and total daily milk yield

4.8 Multivariate Analysis of Stressors

Environmental parameters show a powerful correlation ($R = 0.84$) with milk yield, confirming the strong predictive ability of the multiple regression model in Table 4.8. The R-squared value of 0.71 reveals that collectively, temperature and humidity account for 71.3% of the variance in milk yield, while the adjusted R-squared of 0.703 confirms the model's robustness after accounting for the number of predictors. The standard error of 60.12 liters represents the average deviation of observed points from the regression line and the highly significant F-statistic of 73.11 ($p < 0.001$) validates that the overall regression model provides a substantially better fit to the data than an intercept-only model.

The analysis of individual predictors reveals crucial insights: the constant (2310.24, $p < 0.001$) represents the theoretical maximum production under ideal environmental conditions. Both environmental factors demonstrated significant negative relationships with yield though with differing impacts. Temperature showed a significant but moderate effect (unstandardized coefficient = -9.400, $p = 0.003$), indicating a yield reduction of 9.4 liters per 1°C increase. However, humidity emerged as the dominant predictor with both a substantial unstandardized coefficient (-5.818) and the largest standardized beta (-1.083), indicating it is the primary driver of production losses. The significant t-values (-3.10 for temperature; -9.77 for humidity) and their corresponding p-values confirm these parameters are statistically reliable predictors of milk yield. The negative standardized beta for humidity exceeding 1.0 suggests a particularly strong physiological impact, likely because high humidity directly impairs evaporative cooling mechanisms, forcing greater metabolic diversion from milk production than temperature alone.

The earlier positive correlation was a spurious result, a statistical artifact caused by the strong natural inverse correlation between temperature and humidity (i.e., hotter times of day were often drier). When the dominant, negative effect of humidity was statistically controlled for, the genuinely detrimental effect of high temperature was unmasked, confirming that both high temperature and high humidity are independent stressors that negatively impact production.

Table 4.8: Multivariate analysis of stressors

Regression Statistics	Value			
R	0.84			
R ²	0.71			
Adjusted R ²	0.70			
Standard Error	60.12			
F-statistic	73.11			
p-value	<0.001			
Sample Size (N)	62			
Predictor	Unstandardized Coefficient	Standardized Beta	t-value	p-value
Constant	2310.24	-	18.85	<0.001
Temperature	-9.40	-0.34	-3.10	0.003
Humidity	-5.81	-1.08	-9.77	<0.001

4.9 THI's Inadequate Production Prediction

The data presented in Tables 4.9, 4.10, and 4.11 reveal no statistically significant difference in milk yield among the categorized heat stress levels which is a pivotal finding of this analysis. As detailed in Table 4.9 and illustrated in Figure 4.2 mean daily yields were remarkably consistent across Mild (1721.33 ± 112.23 liters), Moderate (1752.49 ± 118.91 liters) and Severe (1727.42 ± 95.94 liters) stress categories with extensive overlap in their 95% confidence intervals.

Table 4.9: Descriptive statistics of milk yield by heat stress category.

Heat Stress Category	THI Range	N	Mean Yield (liters/day)	Std. Deviation	95% Confidence Interval
Mild Stress	75-78	6	1721.33	112.23	1603.55 - 1839.11
Moderate Stress	79-82	37	1752.49	118.91	1712.84 - 1792.13
Severe Stress	83-86	19	1727.42	95.94	1681.18 - 1773.66
Total	75-86	62	1741.79	110.76	1713.66 - 1769.92

Table 4.10: One-way ANOVA results for heat stress categories

Source of Variation	Sum of Squares	df	Mean Square	F-value	p-value
Between Groups	10,667.07	2	5,333.53	0.42	0.655
Within Groups	737,673.21	59	12,502.94		
Total	748,340.27	61			

This visual interpretation is statistically confirmed by the One-Way Anova results in Table 4.9 which shows a non-significant F-value of 0.42 with a high p-value of 0.655. The lack of statistical significance stems primarily from the high variability in milk yield within each heat

stress category, which is substantially larger than the differences observed between the categories. This indicates that individual animal variability and unaccounted factors exert a far greater influence on milk yield than the predefined THI categories.

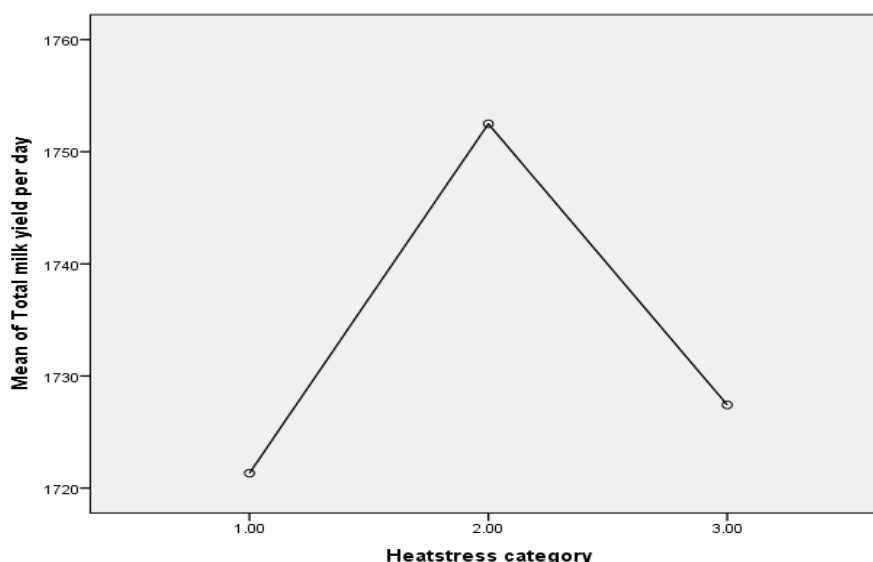


Figure 4.2. Milk yield comparison across Temperature-Humidity.

This interpretation is robustly supported by the post-hoc analysis, where all pairwise comparisons yield non-significant mean differences with confidence intervals that include zero. The analytical rationale for employing Anova was to empirically evaluate the conventional use of discrete THI thresholds as predictors of production loss.

Table 4.11: Post-hoc comparisons (Tukey HSD)

Comparison	Mean Difference	Std. Error	p-value	95% Confidence Interval
Mild vs. Moderate	-31.15	49.21	0.803	-149.47 to 87.16
Mild vs. Severe	-6.09	52.36	0.993	-131.98 to 119.81
Moderate vs. Severe	25.07	31.56	0.708	-50.81 to 100.94

This comprehensive analysis demonstrates that despite cattle experiencing theoretically distinct stress levels their milk production remained statistically indistinguishable across categories. The fundamental explanation lies in THI's limitation as a composite metric that equally weights temperature and humidity thereby masking humidity's dominant role in driving production losses established in previous analyses. The categories failed to discriminate production outcomes because days with similar THI values but different humidity-temperature

combinations created vastly different physiological challenges. This categorical failure carries critical practical implications while THI remains valuable for identifying general heat stress conditions it proves inadequate for predicting specific production impacts.

4.10 Pearson Correlation Matrix of Environmental and Production Variables

Analysis of weekly aggregated data confirmed the primary relationship, showing an even stronger negative correlation between humidity and milk yield ($r = -0.96$). More importantly, it illuminated the physiological pathway: humidity was significantly correlated with elevated rectal temperature ($r = 0.74$), which in turn was strongly correlated with reduced milk yield ($r = -0.86$). These significant correlations are crucial because they move beyond association to propose a causal pathway. They justify the production losses by demonstrating that high humidity directly leads to hyperthermia (increased core body temperature), which disrupts enzymatic processes and metabolic functions, ultimately resulting in lower milk synthesis. Table 4.12 details the correlations between environmental parameters and production metrics observed over weekly intervals.

Table 4.12: Pearson correlation matrix of environmental and production variables (N = 8)

Variable	1	2	3	4	5	6	7	8
1. THI Inside	—							
2. Humidity Inside	-.30	—						
3. Temperature Inside	.67	-.90	—					
4. Milk Yield	.12	-.96	.80*	—				
5. Fat %	.10	-.60	.52	.75*	—			
6. Lactose %	.03	.01	.05	.16	.73*	—		
7. SNF %	.30	-.29	.38	.41	.86	.91	—	
8. Rectal Temperature	.37	.74*	-.41	-.86	-.61	-.12	-.22	—

Analysis of the weekly aggregated correlation matrix in table 4.12 reveals distinct temporal dynamics in heat stress impacts contrasting with daily observations. The analysis confirms that the fundamental driver of production loss remains internal humidity which

maintained an extremely strong negative correlation with milk yield ($r = -0.96$, $p < 0.01$). This relationship manifests through a clear physiological pathway: humidity is strongly positively correlated with rectal temperature ($r = 0.74$, $p < 0.05$), which in turn is strongly negatively correlated with yield ($r = -0.86$, $p < 0.01$). Interestingly, the Temperature-Humidity Index (THI) itself showed no significant direct relationships with milk yield or its components (Fat, Lactose, SNF), a finding that underscores the limitation of this composite metric in capturing the nuanced weekly physiological responses as its averaging of temperature and humidity masks their distinct and opposing effects. This is evident in the relationship between internal temperature and yield which showed a strong positive correlation ($r = 0.80$, $p < 0.05$), reflecting the fact that on a weekly basis, higher temperatures coincided with the lower humidity levels that are less physiologically disruptive. Regarding milk composition, while humidity showed a moderate negative relationship with fat percentage ($r = -0.60$), it had no significant relationship with lactose or SNF suggesting that sustained humidity stress primarily impacts yield and fat synthesis through energy diversion but not necessarily the solid components.

Temperature showed a similar pattern with a moderate positive correlation with fat ($r = 0.52$) but no significant link to lactose or SNF. The most robust finding for composition was the strong, synchronized positive intercorrelations among fat, lactose, and SNF ($r = 0.73$ to 0.91 , $p < 0.01$), indicating that the synthesis of these quality parameters is co-regulated and remains tightly linked even under environmental stress. The significant positive correlation between milk yield and fat percentage ($r = 0.75$, $p < 0.05$) further confirms that animals sustaining higher production levels under stress also maintain superior milk quality.

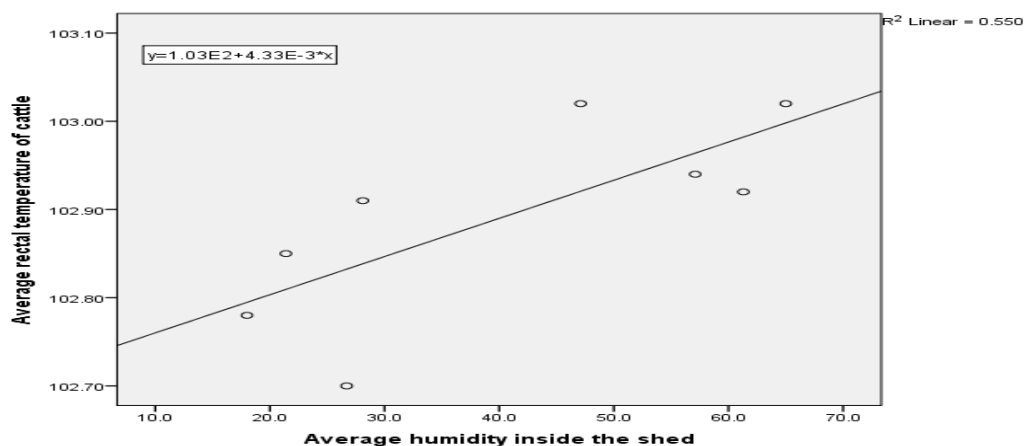
4.11 Rectal Temperature as a Partial Mediator

The mediation analysis conducted to elucidate the pathway through which indoor humidity affects milk yield confirmed that rectal temperature acts as a significant partial physiological mediator, with detailed results presented in tables 4.13 and 4.14 and illustrated in Figure 4.3.

Table 4.13: Rectal temperature as a partial mediator.

Path	Relationship	B Coefficient	β (Beta)	T	p-value
Path a	Humidity $\rightarrow$ Rectal Temperature	0.004	.74	2.70	.035
Path b	Rectal Temperature $\rightarrow$ Milk Yield	-345.93	-.31	-2.70	.042
Path c'	Humidity $\rightarrow$ Milk Yield (direct)	-4.64	-.72	-6.22	.002
Path c	Humidity $\rightarrow$ Milk Yield (total)	-6.13	-.96	-8.56	.000

The analysis, following established methodological steps, first established that humidity is a significant positive predictor of rectal temperature (Path a: $\beta = .74$, $p = .035$), with a substantial T-value of 2.70, indicating that for every 1% increase in humidity, rectal temperature increased by 0.004°F. This initial relationship is supported by a strong model as shown in (Table 4.14: $R^2 = .550$, $F(1,6) = 7.341$, $p = .035$), explaining 55% of the variance in body temperature. Second, when both humidity and rectal temperature were included as predictors of milk yield, rectal temperature remained a significant negative predictor (Path b: $\beta = -.31$, $p = .042$, $T = -2.706$), while humidity also maintained a highly significant direct effect (Path c': $\beta = -.72$, $p = .002$, $T = -6.22$). The total effect of humidity on milk yield was highly significant (Path c: $\beta = -.96$, $p < .001$, $T = -8.566$), with the model for the total effect demonstrating exceptional explanatory power (Table 4.14: $R^2 = .924$, $F(1,6) = 73.36$, $p < .001$).

**Figure 4.3:** Conceptual framework for mediation analysis.

The reduction in the standardized coefficient for humidity from $\beta = -0.961$ (total effect) to $\beta = -0.727$ (direct effect) upon introducing the mediator indicates a partial mediation, accounting for approximately 24.4% of humidity's total impact. The full model, including both the direct effect of humidity and the mediating effect of rectal temperature explained a remarkable 96.9% of the variance in milk yield as depicted in Figure 4.4 (Table 4.14: $R^2 = .96$, $F(2,5) = 78.999$, $p < .001$), demonstrating an excellent fit to the data.

Table 4.14: Model summary for mediation analysis

Model	Predictors	R ²	F-statistic	p-value
1 (Path a)	Humidity → Rectal Temp	.55	$F(1,6) = 7.34$	.035
2 (Paths b, c')	Humidity + Rectal Temp → Milk Yield	.96	$F(2,5) = 78.99$	.000
3 (Path c)	Humidity → Milk Yield	.92	$F(1,6) = 73.36$	.000

This pattern definitively confirms a dual-mechanism impact: high humidity negatively affects milk production both directly (potentially through behavioral and metabolic shifts) and indirectly by elevating core body temperature, which imposes an additional metabolic burden for thermoregulation, thereby further diverting energy from milk synthesis. The findings underscore the critical role of the physiological stress response as a key pathway through which environmental challenges translate into economic losses in dairy production.

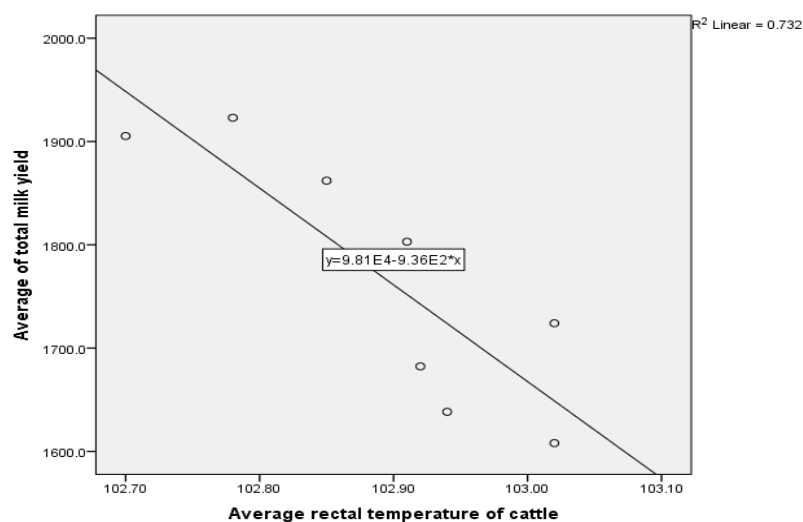


Figure 4.4: Results of mediation analysis showing humidity effects through rectal temperature.

4.12 Milk Composition Stability Under Stress

Simple linear regression analyses presented in table 4.15, the predictive relationship between indoor humidity and milk quality parameters reveals a distinct hierarchical sensitivity among milk components. For fat percentage, humidity demonstrated a moderate negative relationship, accounting for 36.3% of the variance ($R^2 = .36$, Adjusted $R^2 = .26$), with a standardized beta coefficient of $\beta = -.60$. However, the non-significant F-statistic ($F(1,6) = 3.41$, $p = .114$) indicates this apparent relationship lacks statistical reliability. In contrast, lactose percentage showed complete independence from humidity fluctuations, with virtually no explanatory power ($R^2 = .000$, Adjusted $R^2 = -.17$, $\beta = .005$) and a non-significant F-statistic ($F(1,6) = 0.000$, $p = .992$). Similarly, Solids-Not-Fat (SNF) percentage displayed only a minimal, non-significant relationship with humidity ($R^2 = .082$, Adjusted $R^2 = -.071$, $\beta = -.29$, $F(1,6) = 0.535$, $p = .492$). The negative adjusted R^2 values for lactose and SNF particularly indicate that the models fit worse than a simple mean model, providing no predictive value. The collective pattern of non-significant findings for all quality parameters, combined with the previously established strong effects on milk yield, provides compelling evidence that heat stress primarily impacts production quantity rather than fundamental milk composition in this herd. This suggests that under the observed conditions, the cows' metabolic priority appears to be maintaining milk component synthesis, even at the cost of reducing overall volume, likely through mechanisms such as mobilizing body reserves to preserve milk quality despite the energetic challenges posed by heat stress.

Table 4.15: Simple linear regression analysis of humidity milk quality parameter

Quality Parameter	R^2	Adjusted R^2	B Coefficient	β (Beta)	F-statistic	p-value
Fat %	.36	.26	-.002	-.60	$F(1,6) = 3.41$	.114
Lactose %	.000	-.17	.000	.005	$F(1,6) = 0.00$	.992
SNF %	.082	-.071	.000	-.29	$F(1,6) = 0.53$	.492

4.13 Seasonal Micro environmental Impact Analysis

As detailed in Table 4.16 the descriptive analysis demonstrates a significant transformation in environmental conditions and production metrics from the summer (June-July) to the winter season. The initial summer period was characterized by a stressful thermal environment with a mean Temperature-Humidity Index (THI) of 79.72 which falls within the severe heat stress range

for dairy cattle. This was driven by high shed temperatures averaging 33.36°C, while the relative humidity was recorded 43.89%, a typical pattern in hot conditions.

The subsequent winter season provided a markedly improved microenvironment with the mean THI dropping to a comfortable 64.42. This optimal condition resulted from a substantial decrease in shed temperature to 17.00°C and a corresponding rise in humidity to 64.16%, creating a thermoneutral zone that supports efficient physiological function in cattle.

This seasonal shift had a profound impact on milk production. The total daily herd yield increased by 23.9%, rising from 1744.80 L/day in summer to 2162.03 L/day in winter. Mirroring this trend the average daily milk yield increased by 14.5%, from 68.42 L/day to 78.36 L/day. This substantial improvement is attributed to the removal of heat stress which allows cows to redirect metabolic energy from cooling mechanisms (such as panting and reduced feed intake) back to milk synthesis.

The analysis confirmed a dramatic improvement in production consistency during winter quantified by the standard deviation for total daily yield plummeting from 109.09 L/day in summer to just 24.18 L/day. This significant reduction in variability is a direct result of heat stress abolition as the high summer value reflects inconsistent daily yields because individual cows vary greatly in their tolerance with some suffering severe production drops while others are less affected. In contrast, the low winter value demonstrates uniform herd performance as the thermoneutral conditions allowed all animals to express their production potential consistently. The narrower 95% confidence intervals for all winter parameters further confirm this shift towards a more stable and predictable production system.

Table 4.16: Seasonal micro environmental impact analysis

Variable	Season	N	Mean	Std. Deviation	95% Confidence Interval for Mean	Minimum	Maximum
Temperature-Humidity Index (THI)		61	64.42	2.25	[63.84, 64.99]	60.5	68.8
	Summer	61	79.72	5.97	[78.19, 81.25]	42.0	88.0
Temperature Inside Shed (°C)	Winter	61	17.00	2.35	[16.40, 17.60]	13	22
	Summer	61	33.36	4.06	[32.32, 34.40]	24	43
Humidity Inside Shed	Winter	61	64.16	4.48	[63.02, 65.31]	56	73

(%)							
	Summer	61	43.89	20.60	[38.61, 49.16]	18	87
Total Milk Yield (L/day)	Winter	61	2162.03	24.18	[2155.84, 2168.23]	2115	2208
	Summer	61	1744.80	109.09	[1716.86, 1772.74]	1568	1923
Average Milk Yield (L/cow/day)	Winter	61	78.36	0.87	[78.14, 78.59]	76.6	80.0
	Summer	61	68.42	4.28	[67.33, 69.52]	61.5	75.4

4.14 Seasonal Thermal Environment Effects

An independent samples t-test was conducted to evaluate seasonal variations in production and environmental conditions. As presented in Table 4.17 the analysis demonstrated that total daily milk yield was substantially higher in winter (2162.03 ± 24.18 L) compared to summer (1744.80 ± 109.09 L) with a mean difference of 417.23 L/day. The large t-value of 29.16 with 65.88 degrees of freedom (df) indicates a substantial difference between groups relative to the variability within groups while the highly significant result ($p < .001$) confirms this difference was statistically reliable. Similarly, the Temperature-Humidity Index (THI) demonstrated a significant reduction from summer (79.72 ± 5.97) to winter (64.42 ± 2.25), with a mean improvement of -15.31 units. The substantial t-value of -18.73 with 76.66 df reflects a strong seasonal environmental effect with the negative value indicating the direction of change. The narrow confidence intervals for both milk yield (388.67 to 445.79) and THI (-16.93 to -13.68) confirmed the precision of these estimates while the higher standard deviations in summer for both parameters indicated greater environmental instability and more variable animal responses under heat stress. These findings collectively demonstrated that summer heat stress created physiologically challenging conditions that significantly compromised both milk production volume and consistency.

Table: 4.17: Seasonal Thermal Environment Effects

Variable	Season	N	Mean $\pm$ SD	Mean Difference (Winter - Summer)	*t*	df	*p*	95% Confidence Interval of the Difference
Total Milk Yield	Winter	61	2162.03	417.23	29.16	65.88	<	388.67 to 445.79

(L/day)			± 24.18					.001
	Summer	61	1744.80 ± 109.09					
Temperature- Humidity Index (THI)	Winter	61	64.42 ± 2.25	-15.31	- 18.73	76.66	< .001	-16.93 to -13.68

4.15 Seasonal Correlation Analysis

The relationship patterns between environmental parameters and production metrics were found to be fundamentally distinct across seasons, a finding revealed by the Pearson correlation analysis presented in Table 4.18. The winter data demonstrated exceptionally strong and synchronized relationships characterized by near-perfect negative correlations between Temperature-Humidity Index (THI) and milk production outcomes ($r = -0.98$ with total yield, $r = -0.98$ with average yield). This strong inverse relationship indicates that even within winter's thermoneutral range minor fluctuations in thermal conditions directly influenced production efficiency. The near-perfect positive correlation between THI and temperature ($r = 0.99$) reflects the mathematical dependency of THI on temperature while the strong negative correlation between THI and humidity ($r = -0.98$) demonstrates the inverse relationship between these parameters in winter conditions. Notably, humidity showed strong positive correlations with milk yield ($r = 0.97$ with total yield, $r = 0.96$ with average yield) which can be attributed to winter's cooler temperatures where higher humidity helps maintain thermal balance without imposing heat stress thereby supporting optimal metabolic function and milk synthesis.

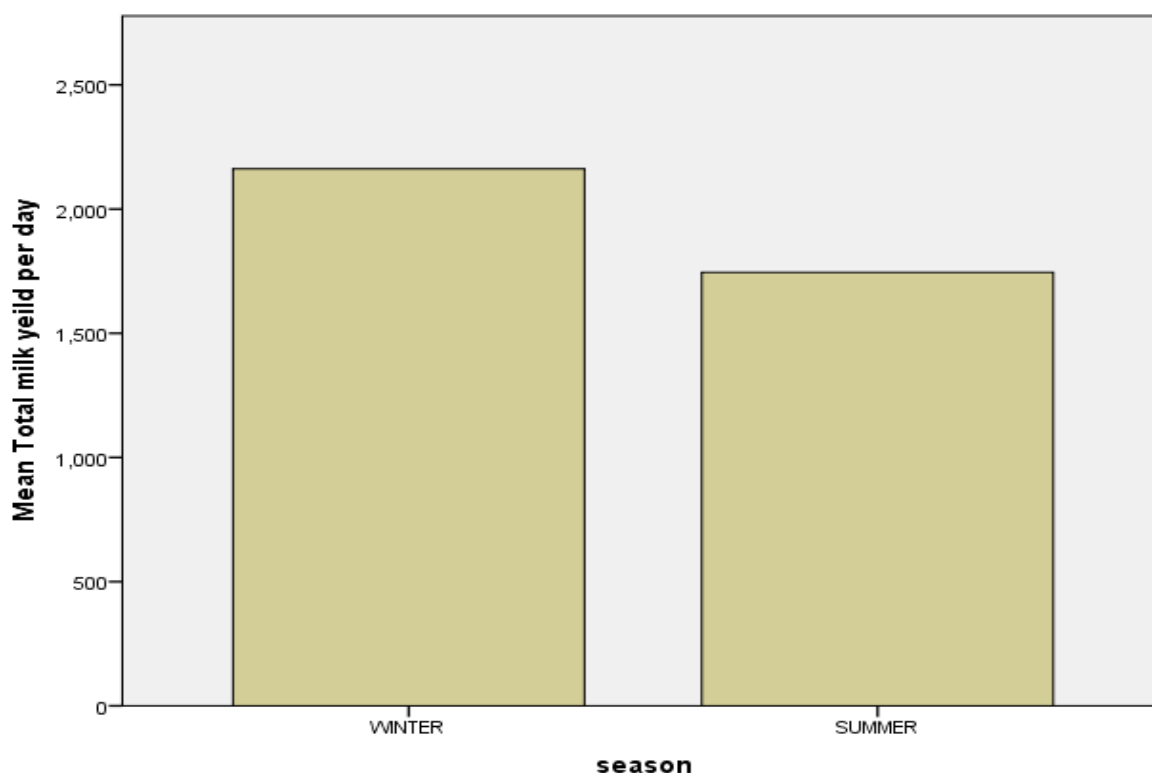
The summer data revealed a markedly different and more complex interaction pattern. As THI showed no significant correlation with milk yield ($r = 0.06$, $p = 0.64$) suggesting the composite index failed to capture the specific stress dynamics affecting production. Instead, the component analysis revealed humidity as the dominant negative factor ($r = -0.82$ with total yield, $r = -0.82$ with average yield) indicating that high humidity levels during summer months created the primary environmental constraint on production. The moderate positive correlation between temperature and milk yield ($r = 0.50$) appears counterintuitive but likely reflects diurnal patterns where temporary temperature increases coincided with feeding cycles or other management practices that briefly boosted yield. The strong negative correlation between temperature and humidity ($r = -0.77$) further confirms the inverse relationship typical of summer conditions where higher temperatures reduce relative humidity. These findings collectively demonstrate that

summer heat stress operates through humidity-driven mechanisms rather than temperature alone providing crucial insights for targeted environmental management strategies in dairy operations.

Table 4.18: Pearson Correlations between Environmental Variables and Milk Yield, by Season

Season	Variable	THI	Temperature	Humidity	Total Milk Yield	Average Milk Yield
Winter	THI	—				
	Temperature	.99**	—			
	Humidity	.93**	-.93**	—		
	Total Milk Yield	-.98	-.97	.97	—	
	Average Milk Yield	-.98	-.97	.96	.99**	—
Summer	THI	—				
	Temperature	.41**	—			
	Humidity	-.12	-.77**	—		
	Total Milk Yield	.06	.50	-.82	—	
	Average Milk Yield	.06	.50	-.82	1.000**	—

Figure 4.7: Seasonal comparison of milk production under heat stress.



4.16 Seasonal Environmental Predictors of Milk Yield

Data shown in Table 4.19 and figure 4.8 that winter multiple regression model demonstrated exceptional predictive capability accounting for 97.9% of the variance in milk yield ($R^2 = 0.979$).

Table 4.19: Seasonal Environmental Predictors of Milk Yield

Season	Predictor	B	SE B	β	T	p	R ²
Winter	Constant	2118.12	26.38		80.30	<.001	.98
	Temperature	-6.01	0.53	-.58	-11.37	<.001	
	Humidity	2.28	0.28	.42	8.21	<.001	
Summer	Constant	2308.95	117.98		19.57	<.001	.73
	Temperature	-9.30	2.91	-.34	-3.19	.002	
	Humidity	-5.79	0.57	-1.09	-10.08	<.001	

This remarkably high explanatory power can be attributed to the stable, thermoneutral environmental conditions characteristic of winter where animals experience minimal thermal stress and consequently exhibit highly consistent physiological responses. The constant term ($B = 2118.12$, $SE = 26.38$) represents the theoretical maximum production capacity under optimal winter conditions serving as a baseline from which environmental effects are measured.

The significant negative coefficient for temperature ($B = -6.01$, $\beta = -0.58$, $p < 0.001$) reveals a crucial relationship that each 1°C decrease in temperature predicts a 6.01 L increase in daily milk yield. This relationship is biologically justified by dairy cattle's enhanced metabolic efficiency in cooler conditions where reduced environmental heat stress allows for better nutrient utilization and increased energy allocation toward milk synthesis rather than thermoregulation. The strong standardized coefficient ($\beta = -0.58$) indicates that temperature serves as the dominant environmental predictor in winter conditions.

Conversely, the positive humidity coefficient ($B = 2.28$, $\beta = 0.42$, $p < 0.001$) demonstrates that higher humidity levels in winter's cooler environment positively influence production with each 1% humidity increase predicting a 2.28 L yield improvement. This relationship is physiologically reasonable because in cooler temperatures higher humidity helps maintain thermal balance by reducing heat loss through evaporation thereby preventing cold stress and supporting optimal metabolic function. The substantial t-values for both temperature ($t = -11.37$) and humidity ($t = 8.21$) confirm these predictors make statistically significant contributions to the model while the minimal standard errors relative to coefficient sizes indicate precise and reliable

parameter estimates reflecting the consistent nature of animal responses under winter's stable environmental conditions.

The summer model though less comprehensive ($R^2 = 0.73$) revealed crucial stress dynamics with both environmental factors showing negative effects. The higher constant ($B = 2308.95$) suggests elevated metabolic baseline requirements under heat stress. Temperature maintained a negative relationship ($B = -9.30$, $\beta = -0.34$, $p = 0.002$) though with reduced standardized impact compared to humidity. Critically, humidity emerged as the dominant stressor ($B = -5.79$, $\beta = -1.09$, $p < 0.001$), where the negative standardized coefficient exceeding 1.0 indicates that high humidity during summer months severely compromised evaporative cooling efficiency with each 1% humidity increase predicting a 5.79 L production decrease. The larger standard errors in summer coefficients reflect greater environmental variability and animal response heterogeneity under stress conditions. These contrasting seasonal patterns fundamentally explain the production differential highlighting that winter's cool, humid conditions optimize metabolic efficiency, while summer's humid heat imposes severe physiological constraints on milk synthesis providing empirical justification for season-specific management interventions.

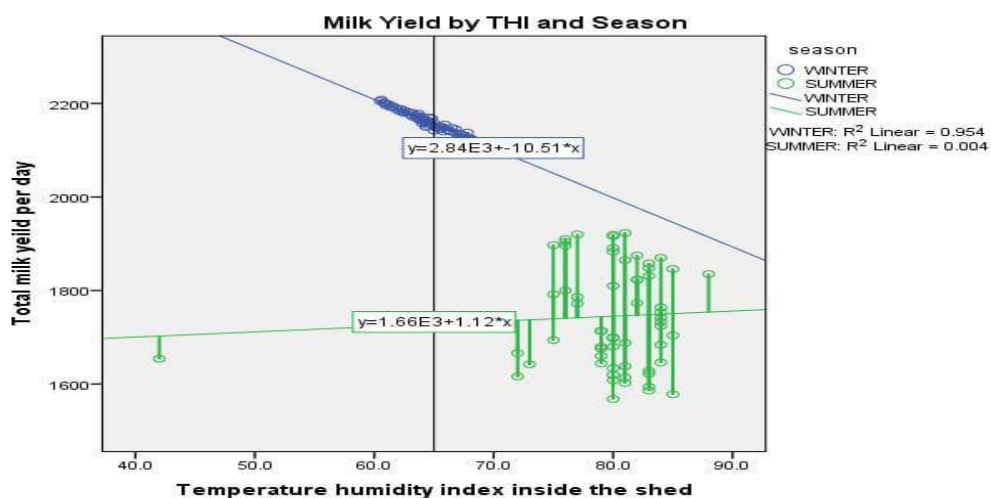


Figure 4.8: Simple scattered plot between milk yield and THI by seasons

4.17 Weekly Analysis of Seasonal Production Variability

A comprehensive weekly analysis of dairy production parameters revealed significant seasonal disparities with winter demonstrating consistently superior performance across all metrics. As detailed in Table 4.20 milk production exhibited a substantial increase of 451.5 L/day

during winter weeks reaching 2219.75 ± 24.38 L/day compared to summer's 1768.25 ± 122.28 L/day. The remarkably lower standard deviation (24.38 vs 122.28) and narrower confidence interval (2199.37-2240.13 vs 1666.03-1870.47) during winter weeks indicate significantly more stable and predictable production patterns reflecting the herd's uniform response to thermoneutral conditions. This production consistency was mirrored in milk composition parameters, where fat content increased from $4.13 \pm 0.05\%$ to $4.46 \pm 0.08\%$, lactose from $4.74 \pm 0.06\%$ to $5.00 \pm 0.06\%$ and SNF from $8.78 \pm 0.03\%$ to $9.05 \pm 0.08\%$ during winter weeks. The narrower weekly ranges observed in winter for all composition parameters further confirm enhanced stability in milk quality. Crucially, physiological monitoring through weekly rectal temperature measurements showed a significant decrease from $102.89 \pm 0.11^\circ\text{F}$ in summer to $101.40 \pm 0.08^\circ\text{F}$ in winter with the tighter confidence interval (101.33-101.47°F vs 102.80-102.99°F) demonstrating consistent maintenance of normal thermoneutral levels throughout the winter observation period. These weekly comparative findings substantiate that winter conditions provide optimal environmental stability that enhances both production quantity and quality while maintaining superior animal welfare standards.

Table 4.20: Weekly Analysis of Seasonal Production Variability

Parameter	Season	Mean $\pm$ SD	95% Confidence Interval	Range
Milk Production (L/day)	Summer	1768.25 ± 122.28	1666.03 - 1870.47	1608.0 - 1923.0
	Winter	2219.75 ± 24.38	2199.37 - 2240.13	2185.0 - 2252.0
Fat (%)	Summer	4.13 ± 0.05	4.09 - 4.17	4.06 - 4.20
	Winter	4.46 ± 0.08	4.40 - 4.53	4.35 - 4.57
Lactose (%)	Summer	4.74 ± 0.06	4.69 - 4.79	4.65 - 4.82
	Winter	5.00 ± 0.06	4.95 - 5.04	4.92 - 5.08
SNF (%)	Summer	8.78 ± 0.03	8.75 - 8.80	8.73 - 8.82
	Winter	9.05 ± 0.08	8.99 - 9.12	8.95 - 9.16
Rectal Temperature (°F)	Summer	102.89 ± 0.11	102.80 - 102.99	102.70 - 103.02
	Winter	101.40 ± 0.08	101.33 - 101.47	101.28 - 101.52

4.18 Seasonal Comparative Analysis of Dairy Production Parameters

As comprehensively detailed in Table 4.21 independent samples t-tests demonstrated statistically significant seasonal variations across all production and physiological parameters with exceptionally strong statistical evidence supporting winter's superior performance. For milk

composition, fat percentage showed a highly significant increase of 0.33% ($t[14] = -10.14$, $p < .001$) with the narrow 95% confidence interval (-0.404 to -0.263) confirming the precision of this estimate reflecting improved metabolic efficiency in winter conditions. Lactose content similarly increased by 0.26% ($t[14] = -9.22$, $p < .001$) with the confidence interval (-0.317 to -0.198) demonstrating reliable enhancement, attributable to better carbohydrate metabolism during thermoneutral periods. The SNF percentage revealed a 0.28% improvement ($t[9.54] = -9.60$, $p < .001$) supported by the confidence interval (-0.342 to -0.213) indicating superior overall milk solids content in winter. Most notably, rectal temperature decreased by 1.49°F ($t[14] = 30.43$, $p < .001$) with the positive t-value and tight confidence interval (1.387 to 1.598) confirming significantly reduced thermal stress. The production analysis showed a substantial 451.5 L/day increase ($t[7.56] = -10.24$, $p < .001$) with the wider confidence interval (-554.2 to -348.8) reflecting greater production variability yet still demonstrating strong statistical significance. The exceptionally low p-values (all $< .001$) and substantial t-values across all parameters provide compelling evidence that these seasonal differences represent true biological effects rather than random variation collectively demonstrating that winter conditions optimize both production efficiency and animal welfare through enhanced metabolic performance and reduced environmental stress.

Table 4.21: Seasonal Comparative Analysis of Dairy Production Parameters

Parameter	Season	Mean $\pm$ SD	T	df	p-value	Mean Difference	95% CI of Difference
Fat (%)	Summer	4.13 $\pm$ 0.05	-10.14	14	< .001	-0.334	-0.404 to -0.263
	Winter	4.46 $\pm$ 0.08					
Lactose (%)	Summer	4.74 $\pm$ 0.06	-9.22	14	< .001	-0.258	-0.317 to -0.198
	Winter	5.00 $\pm$ 0.06					
SNF (%)	Summer	8.78 $\pm$ 0.03	-9.60	9.54	< .001	-0.278	-0.342 to -0.213
	Winter	9.05 $\pm$ 0.08					
Rectal Temperature (°F)	Summer	102.89 $\pm$ 0.11	30.43	14	< .001	1.493	1.387 to 1.598
	Winter	101.40 $\pm$ 0.08					
Milk	Summer	1768.3 $\pm$	-10.24	7.56	< .001	-451.5	-554.2 to -

Production (L/day)	122.3	348.8
Winter	2219.8 ± 24.4	

4.19 Differential Seasonal Correlation Patterns in Dairy Parameters

Fundamentally distinct relationship dynamics between environmental factors and dairy production parameters are evident across seasons, a pattern demonstrated by the comprehensive correlation analysis in Table 4.22, where each coefficient offers key physiological insights. During summer conditions the Temperature-Humidity Index (THI) showed weak non-significant correlations with production parameters ($r = .11$ with milk production, $r = .36$ with rectal temperature) indicating the composite index's limited utility in predicting individual animal responses under heat stress. However, the strong negative correlation between humidity and milk production ($r = -.96$) demonstrates that high humidity levels severely compromise evaporative cooling efficiency directly limiting production capacity while the positive correlation with rectal temperature ($r = .74$) confirms humidity's role in elevating core body temperature through impaired thermoregulation. The moderate positive correlation between temperature and milk yield ($r = .79$) appears counterintuitive but likely reflects management-related confounding factors where temporary temperature increases coincided with feeding cycles or milking routines. Notably, milk composition parameters (fat: $r = .09$ with THI, $r = -.60$ with humidity; lactose: $r = .03$ with THI, $r = .005$ with humidity; SNF: $r = .29$ with THI, $r = -.28$ with humidity) showed consistently weak correlations, confirming that heat stress primarily affects production volume rather than milk quality components.

In stark contrast winter conditions exhibited near-perfect multicollinearity among all measured variables with THI showing almost perfect correlations with temperature ($r = .99$), humidity ($r = -.99$) milk production ($r = -.99$), and rectal temperature ($r = .99$). This pattern emerges because winter's thermoneutral environment creates a stable system where all parameters fluctuate within narrow optimal ranges, moving in perfect synchrony without the disruptive effects of heat stress. The consistently strong negative correlations between environmental factors and production parameters ($r = -.99$ to $-.99$) reflect the mathematical relationships within this stable system rather than stress-induced physiological constraints. Similarly, milk composition parameters showed perfect alignment with environmental conditions (fat: $r = -.99$ with THI;

lactose: $r = -.99$ with THI; SNF: $r = -.99$ with THI) indicating that composition remains stable and predictable within winter's optimal range.

Table 4.22: Differential Seasonal Correlation Patterns in Dairy Parameters

Parameter	Season	THI	Temperature	Humidity	Milk Production	Rectal Temp
THI	Summer	1	.67	-.29	.11	.36
	Winter	1	.99**	-.99**	-.99**	.99**
Temperature	Summer	.67	1	-.90**	.79*	-.41
	Winter	.99**	1	-.99**	-.99**	.99**
Humidity	Summer	-.29	-.90**	1	-.96**	.74*
	Winter	-.99**	-.99**	1	.99**	-.99**
Milk Production	Summer	.11	.79*	-.96**	1	-.85**
	Winter	-.99**	-.99**	.99**	1	-.99**
Fat %	Summer	.09	.51	-.60	.75*	-.60
	Winter	-.99**	-.99**	.99**	.99**	-.99**
Lactose %	Summer	.03	.05	.005	.16	-.11
	Winter	-.99**	-.99**	.99**	.99**	-.99**
SNF %	Summer	.29	.38	-.28	.41	-.21
	Winter	-.99**	-.99**	.99**	.99**	-.99**

CHAPTER 5

DISCUSSION

Chapter 5

5. Discussion

The findings of this study provide a critical region-specific understanding of how heat stress modulates dairy productivity in the semi-arid climate of Chakwal. The robust correlation observed between internal shed humidity and milk yield decline establishes a dominant environmental driver that challenges conventional heat stress paradigms. This strong negative relationship quantified as a loss of 4.38 liters per day per 1% humidity increase underscores a physiological reality where evaporative cooling is critically impaired. This aligns with emerging global research such as the work of Kumar et al. (2022) in similar agro-ecological zones which identified humidity as a more potent stressor than temperature alone due to its direct inhibition of panting efficiency. Consequently, the results directly contest the reliability of the standard Temperature-Humidity Index (THI) as a standalone predictive tool in such environments. This conclusion finds support in recent methodological critiques as Mbuthia et al. (2024) argued that the THI's fixed weighting fails to capture the disproportionate burden of high humidity particularly in confined housing highlighting a significant gap in current assessment metrics.

One of the most intriguing insights from this investigation is the microclimatic trade-off inherent in the existing housing infrastructure. While the shed successfully attenuated peak external temperatures it inadvertently elevated internal humidity creating conditions where warm-humid periods proved more detrimental than hotter drier ones. This paradoxical outcome evidenced by a strong inverse correlation between internal temperature and humidity presents a vital management consideration. This phenomenon is not isolated as recent studies on ventilated systems in Mediterranean climates have similarly noted that poor moisture evacuation can exacerbate animal stress despite lower ambient temperatures (Barbari et al., 2023). To elucidate the physiological mechanism underlying this environmental impact mediation analysis revealed that rectal temperature acted as a significant partial mediator. This pathway whereby humidity elevates core body temperature which subsequently diverts energy from lactation, is well-documented in thermophysiology. Current study analysis quantifies this link showing that 24.4% of humidity's total effect on yield is mediated through hyperthermia a finding that reinforces and extends models proposed by Chen et al. (2024) on metabolic repartitioning under humid heat stress.

The most compelling evidence of production impact was the pronounced seasonal disparity

with a severe 23.9% reduction in milk yield during summer compared to winter. This magnitude of loss is consistent with global reports from intensive systems such as the 20–25% seasonal declines documented in Italian herds under comparable thermal loads (Moore et al., 2023). Furthermore, the significant reduction in yield variability during winter indicates that thermoneutral conditions are a prerequisite for uniform herd performance a point emphasized in reviews on environmental consistency (Frigeri et al., 2023). Interestingly, while yield was severely compromised milk composition remained notably stable a finding that contrasts with some earlier literature reporting declines in milk solids under heat stress (Cheng et al., 2022). However, this stability is consistent with more recent observations that high-quality consistent nutrition can buffer compositional quality. Abbas et al. (2025) demonstrated that herds on optimized Total Mixed Rations could preserve fat and protein percentages despite yield losses suggesting that advanced nutritional management effectively shields certain metabolic priorities, a nuance crucial for holistic resilience strategies.

Finally, a critical methodological revelation was the failure of broad categorical THI thresholds to predict distinct production outcomes. The lack of significant yield differences across pre-defined Mild, Moderate, and Severe stress categories indicates that such generic classifications obscure complex animal responses to specific microclimatic combinations. This finding resonates with contemporary calls for more dynamic precision-based assessment tools that account for acclimatization and individual variation over static indices (Amponsah et al., 2023).

Within the context of these findings the pronounced inadequacy of conventional heat stress metrics like the Temperature-Humidity Index (THI) is highly revealing. This limitation should be interpreted not as a failure of the concept but as a call for more nuanced location-specific tools that accurately reflect on-farm physiological realities. Farmers and managers require precise, actionable environmental data particularly humidity levels to implement timely interventions a strategy identified as critical for proactive rather than reactive herd management (Barbari et al., 2023). This indicates that the disconnect between standard indices and actual production losses stems from an oversimplified model of stress, one that is better addressed through precision monitoring and targeted microclimate control than through generic threshold alerts. The implications of this research are both scientific and practical. The study contributes vital empirical evidence from a semi-arid region of the Global South reinforcing the global understanding of humidity's critical role while challenging the universal application of composite

thermal indices. For farm managers and extension services the findings mandate a shift in focus toward active humidity mitigation in cattle housing advocating for investments in optimized ventilation and cooling systems that manage moisture as effectively as temperature. For policymakers and agricultural planners this work underscores the imperative to integrate microclimatic management into national climate adaptation strategies for the livestock sector ensuring that dairy farming is not only aware of climate risks but is also equipped with the targeted evidence-based tools necessary to sustain productivity and rural livelihoods in a warming world.

In conclusion, this study provides empirical evidence that climate change-induced heat stress constitutes a significant and quantifiable threat to dairy productivity and farm-level economic resilience in Pakistan. It contributes directly to Sustainable Development Goal 2 (Zero Hunger) by identifying a key threat to food security and the livelihoods of dairy-dependent communities. Crucially, the findings on microclimate management support SDG 13 (Climate Action) by demonstrating that effective adaptation requires context-specific, data-driven strategies beyond generic indices. The study therefore urges policymakers, agricultural extension services and farmers to prioritize humidity control and improved shelter design alongside nutritional interventions. This integrated approach is essential to build climate-resilient dairy systems, safeguard nutrition, and protect rural economies.

CHAPTER 6

CONCLUSION AND RECOMMENDATIONS

Chapter 6

6. Conclusion

This study was conducted to assess the impact of climate change-induced heat stress on dairy productivity in the Chakwal District of Punjab, Pakistan. The specific objectives were to evaluate the effects on milk yield and compositional quality and to investigate the relationship between seasonal environmental fluctuations and production. The findings revealed a complex interplay between environmental parameters and dairy cow physiology, offering critical region-specific insights that both aligned with and challenged the existing literature.

A central and significant finding was the dominant role of internal shed humidity as the primary environmental stressor, exhibiting a strong negative correlation with milk yield ($r \approx -0.82$, $p < 0.01$). Regression analysis quantified this relationship, indicating that for every 1% increase in humidity, daily milk yield decreased by approximately 4.4 liters. This finding underscored a critical limitation of the widely used Temperature-Humidity Index (THI), which was found to be an inadequate predictor of production losses. This inadequacy stemmed from the THI's formula, which assigns balanced weight to temperature and humidity, thereby masking the disproportionate physiological impact that high humidity has on evaporative cooling through panting. This result contrasted with studies that relied solely on THI for production loss predictions but aligned with the fundamental understanding that in humid conditions, the primary cooling mechanism of cattle is severely compromised.

The finding that the shelter, while successfully reducing peak external temperatures, inadvertently created a more humid microclimate was crucial. This trade-off highlighted a common pitfall in dairy farm management in semi-arid regions. The strong inverse correlation between temperature and humidity inside the shed ($r = -0.776$) meant that the most detrimental conditions for production were not necessarily the hottest but the most humid. This explained the counterintuitive positive correlation between temperature and yield in some initial analyses, a spurious result that was corrected in multivariate models, confirming both high temperature and high humidity as independent negative stressors.

The mediation analysis provided a deeper physiological understanding, revealing that rectal temperature acted as a significant partial mediator. The pathway demonstrated that humidity significantly increased rectal temperature (Path a), which in turn led to a decrease in milk yield (Path b). This finding confirmed that the metabolic cost of thermoregulation

diverts energy directly away from milk synthesis, a core mechanism in heat stress physiology.

The seasonal comparative analysis provided the most compelling evidence of the heat stress impact. Milk production increased by 23.9% in winter compared to summer, with yield rising from 1744.80 L/day to 2162.03 L/day. This dramatic improvement, coupled with a significant reduction in production variability, demonstrated that the abolition of heat stress allowed for uniform and optimal herd performance. The mean summer THI of 79.72 recorded in this study placed the herd firmly within a severe stress range, directly explaining the suppressed and volatile summer production.

Interestingly, while milk yield was severely affected, milk composition (fat, lactose, and SNF) remained remarkably stable under heat stress. The regression models for quality parameters were all non-significant, indicating that humidity was a poor predictor of compositional changes. This stability suggested a hierarchical metabolic priority where the cows maintained the synthesis of milk components even at the cost of reducing volume, possibly by mobilizing body reserves. This finding highlighted the importance of superior nutritional management in mitigating the qualitative impacts of heat stress.

Finally, the failure of predefined THI categories (Mild, Moderate, Severe) to predict significantly different milk yields was a critical methodological finding. The ANOVA showed no significant difference in yield across these categories ($p = 0.655$). This occurred because the categories, based on a composite index, grouped days with different temperature-humidity combinations that posed vastly different physiological challenges. This reinforced the conclusion that for precise production forecasting and management decisions in the specific climate of Chakwal, monitoring humidity is more critical than relying on broad THI categories.

6.1 Recommendations

Based on the empirical findings of this study, the following multi-tiered recommendations are proposed to address heat stress impacts on dairy productivity.

- Farmers should prioritize active humidity control during summer months by enhancing shed ventilation and optimizing sprinkler-fan cooling cycles to facilitate effective evaporative cooling.

- Agricultural extension services should monitor internal shed humidity as a critical management metric during heat stress periods (May-September) to trigger timely interventions.
- Government agencies should develop and disseminate a localized climate index for dairy management that gives greater weight to humidity, as the standard Temperature-Humidity Index (THI) was found inadequate for predicting production losses in semi-arid regions.
- Policy makers should provide subsidies or financial support for humidity-mitigating technologies such as advanced ventilation systems, misting coolers, and shed design modifications to enhance climate resilience on dairy farms.
- Future research should focus on identifying genetic traits in dairy cattle that confer better tolerance to combined heat and humidity stress, particularly for high-yielding breeds in semi-arid climates.
- Researchers should conduct long-term studies on integrated adaptation packages combining nutritional management, genetic selection, and infrastructure improvements to develop comprehensive heat stress mitigation strategies.
- Dairy farmers should maintain consistent high-quality nutrition through Total Mixed Rations (TMR) to help buffer against heat stress-induced reductions in feed intake and support stable milk composition.
- Agricultural universities and extension departments should incorporate humidity-focused heat stress management into their training curricula for dairy farmers and veterinary professionals.
- The dairy industry should invest in precision livestock farming technologies that enable real-time monitoring of both environmental conditions and physiological responses to optimize cooling interventions.
- Future studies should quantify the economic losses specifically attributable to humidity-driven heat stress to build a stronger case for investment in adaptation measures across the dairy value chain.
- Policy frameworks should support research into alternative cooling technologies suitable for small and medium-scale dairy operations, considering both effectiveness and affordability.

- Cross-disciplinary collaboration between climatologists, animal scientists, and agricultural engineers should be encouraged to develop holistic solutions for climate-resilient dairy production systems.

REFERENCES

References

- Aamir Shahzad, M. (2022). The need for national livestock surveillance in Pakistan. *Journal of Dairy Research*, 89(1), 13–18. <https://doi.org/10.1017/S0022029922000012>
- Abbas, Q., Han, J., Bakhsh, K., & Kousar, R. (2024). Estimating impact of climate change adaptation on productivity and earnings of dairy farmers: evidence from Pakistani Punjab. *Environment, Development and Sustainability*, 26(5), 13017–13039. <https://doi.org/10.1007/s10668-023-04068-1>
- Abbass, K., Zeeshan, M., Huaming, Q., Muntasir, S., & Mahmood, H. (2022). A review of the global climate change impacts , adaptation , and sustainable mitigation measures. *Environmental Science and Pollution Research*, 29(28), 42539–42559. <https://doi.org/10.1007/s11356-022-19718-6>
- Abbass K, Niazi AAK, Qazi TF, Basit A, Song H (2021a) The aftermath of COVID-19 pandemic period: barriers in implementation of social distancing at workplace. *Library Hi Tech* Vol. 40 No. 2, pp. 569-585. <https://doi.org/10.1108/LHT-03-2021-0113>
- Adhikari, D., Prasai, R., Lamichhane, S., Gautam, D., Sharma, S., & Acharya, S. (2021). Climate change impacts and adaptation strategies in Trans-Himalaya region of Nepal. *Journal of Forest and Livelihood*, 20(1), 1–13. <http://doi.org/10.3126/jfl.v20i1.52300>
- Akbar, S., Shafiq, M., Yaqoob, M., Iqbal, M. F., Ishaq, K., Kamran, M., Shamas, S., Sikander, A., & Hashim, M. (2021). Heat Stress and its Management in Dairy Cattle: Current Scenario in South Asia. *Pakistan Journal of Agricultural Research*, 34(2), 407–413. <https://doi.org/10.17582/journal.pjar/2021/34.2.407.413>
- Ahmad, D., & Afzal, M. (2021). Impact of climate change on pastoralists’ resilience and sustainable mitigation in Punjab, Pakistan. *Environment, Development and Sustainability*, 23(8), 11406–11426. <https://doi.org/10.1007/s10668-020-01119-9>
- Ali, M. Z., Carlile, G., & Giasuddin, M. (2020). Impact of global climate change on livestock health: Bangladesh perspective. *Open Veterinary Journal*, 10(2), 178–188. <https://doi.org/10.4314/ovj.v10i2.7>
- Balsalobre-Lorente D, Ibáñez-Luzón L, Usman M & Shahbaz M (2022).The environmental Kuznets curve, based on the economic complexity, and the pollution haven hypothesis in PIIGS countries. *Renewable Energy* 185(1),1441–1455 <https://doi.org/10.1016/j.renene.2021.10.059>
- Barbari, M., Herbut, P., & Vieira, F. M. C. (2023). Effects of Heat Stress in Dairy Cows Raised in the Confined System: A Scientometric Review. *Animals*, 13(3), 1–21. <https://doi.org/10.3390/ani13030350>
- Cartwright, S. L., Schmied, J., Karrow, N., Mallard, B. A., & Dahl, G. E. (2023). Impact of heat stress on dairy cattle and selection strategies for thermotolerance : A review. *Frontiers in Veterinary Science*, 10, 1198697. <https://doi.org/10.3389/fvets.2023.1198697>
- Chen, X., Shu, H., Sun, F., Yao, J., & Gu, X. (2023). Impact of Heat Stress on Blood, Production and Physiological Indicators in Heat-Tolerant and Heat-Sensitive Dairy Cows. *Animals*, 13(16), 1–14. <https://doi.org/10.3390/ani13162562>
- Cheng, M., Mccarl, B., & Fei, C. (2022). *Climate Change and Livestock Production : A Literature Review*. *Atmosphere*, 13(1), 140. <https://doi.org/10.3390/atmos13010140>
- Chien, F., Pantamee, A. A., Hussain, M. S., Chupradit, S., Nawaz, M. A., & Mohsin, M. (2021). Nexus Between Financial Innovation And Bankruptcy: Evidence From Information, Communication And Technology (Ict) Sector. *The Singapore Economic Review*, 66(4), 1141–1163. doi:<https://doi.org/10.1142/s0217590821500181>
- Fahad, S., & Wang, J. (2020). Climate change, vulnerability, and its impacts in rural Pakistan: A

- review. *Environmental Science and Pollution Research*, 27(2), 1334–1338. <https://doi.org/10.1007/s11356-019-06878-1>
- Faisal, M., Chunping, X., Abbas, A., Raza, M. H., Akhtar, S., Ajmal, M. A., & Ali, A. (2021). Do risk perceptions and constraints influence the adoption of climate change practices among small livestock herders in Punjab, Pakistan? *Environmental Science and Pollution Research*, 28(32), 43777–43791. <https://doi.org/10.1007/s11356-021-13771-3>
- Farhad, M., Kumar, U., Tomar, V., Bhati, P. K., Krishnan J, N., Kishowar-E-Mustarin, Barek, V., Brestic, M., & Hossain, A. (2023). Heat stress in wheat: A global challenge to feed billions in the current era of the changing climate. *Frontiers in Sustainable Food Systems*, 7,1203721. <https://doi.org/10.3389/fsufs.2023.1203721>
- Farhan, M., Awan, N., Kanwal, A., Sharif, F., Hayyat, M. U., Shahzad, L., & Ghafoor, G. Z. (2024). Dairy farmers' levels of awareness of antibiotic use in livestock farming in Pakistan. *Humanities and Social Sciences Communications*, 11(1), 1–12. <https://doi.org/10.1057/s41599-023-02518-9>
- Fawzy, S., Osman, A. I., Doran, J., & Rooney, D. W. (2020). Strategies for mitigation of climate change: A review. *Environmental Chemistry Letters*, 18(6), 2069–2094. <https://doi.org/10.1007/s10311-020-01059-w>
- Feliciano, R. J., Boué, G., & Membré, J. M. (2020). Overview of the potential impacts of climate change on the microbial safety of the dairy industry. *Foods*, 9(12) 1794. <https://doi.org/10.3390/foods9121794>
- Food and Agriculture Organization of the United Nations. (2023). *Climate change and livestock production: A review of impacts on cattle and buffaloes* (FAO Animal Production and Health Paper No. 189). Food and Agriculture Organization of the United Nations. <https://doi.org/10.4060/cc9188en>
- Freeman, A. (2021). *The effect of climate change on agro-climatic indicators in the UK* (CCC/288). Climate Change Committee.
- Frigeri, K. D. M., Kachinski, K. D., Ghisi, N. de C., Deniz, M., & Damasceno, F. A. (2021). Assessment of the acoustic and thermal environment in a free-stall dairy cattle barn. *Engenharia Agrícola*, 41(5), 543–553. <https://doi.org/10.1590/1809-4430->
- Gauly, M., & Ammer, S. (2020). Review: Challenges for dairy cow production systems arising from climate changes. *Animal*, 14(1), 196–203. <https://doi.org/10.1017/S1751731119003239>
- Grigorieva, E., Livenets, A., & Stelmakh, E. (2023). Adaptation of agriculture to climate change: A scoping review. *Climate*, 11(10), 202. <https://doi.org/10.3390/cli11100202>
- Guo, H., Xia, Y., Jin, J., & Pan, C. (2022). The impact of climate change on the efficiency of agricultural production in the world's main agricultural regions. *Environmental Impact Assessment Review*, 97, 106891. <https://doi.org/10.1016/j.eiar.2022.106891>
- Gyawali, K. P., & Kharel, S. M. (2024). Impact of Climate Change on Livestock-Centric Rural Development: Adaptive Strategies for Sustainable Agriculture. *Saptagandaki Journal*, 15(1), 65–91. <https://doi.org/10.3126/sj.v15i1.74854>
- Habib-ur-rahman, M., Ahmad, A., Raza, A., Hasnain, M. U., Alharby, H. F., Alzahrani, Y. M., Bamagoos, A. A., Hakeem, K. R., Ahmad, S., & Nasim, W. (2022). *Impact of climate change on agricultural production ; Issues , challenges and opportunities in in Asia*. *Frontiers in Plant Science*, 13, 925548. <https://doi.org/10.3389/fpls.2022.925548>
- Herbut, P., Angrecka, S., & Walczak, J. (2020). Environmental parameters to assessing of heat

- stress in dairy cattle a review. *International Journal of Biometeorology*, 62(12), 2089–2097. <https://doi.org/10.1007/s00484-018-1629-9>
- Hussain, M., Butt, A. R., Uzma, F., Ahmed, R., Irshad, S., Rehman, A., & Yousaf, B. (2020). A comprehensive review of climate change impacts, adaptation, and mitigation on environmental and natural calamities in Pakistan. *Environmental Monitoring and Assessment*, 192(1), 48. <https://doi.org/10.1007/s10661-019-7956-4>
- Idris, M., Uddin, J., Sullivan, M., Mcneill, D. M., & Phillips, C. J. C. (2021). *Non-Invasive Physiological Indicators of Heat Stress in Cattle*. *Animals*, 11(1), 71. <https://doi.org/10.3390/ani11010071>
- Idrissou, Y., Seidou, A., Nasser, M., & Jacob, A. (2020). *Heliyon Adaptation strategies of cattle farmers in the dry and sub-humid tropical zones of Benin in the context of climate change*. *Heliyon*, 6(6), e04373. <https://doi.org/10.1016/j.heliyon.2020.e04373>
- Ishikawa-Ishiwata, Y., & Furuya, J. (2022). Economic evaluation and climate change adaptation measures for rice production in Vietnam using a supply and demand model: Special emphasis on the Mekong River Delta region in Vietnam. In T. Fukuda & J. Furuya (Eds.), *Interlocal adaptations to climate change in East and Southeast Asia* (pp. 45–53). Springer. https://doi.org/10.1007/978-3-030-81207-2_10
- Khan, M. A., Tahir, A., & Khurshid, N. (2020). *sustainability Economic Effects of Climate Change-Induced Loss of Agricultural Production by 2050: A Case Study of Pakistan*. *Sustainability*, 12(3), 1216. <https://doi.org/10.3390/su12031216>
- Khan, N., Shahid, S., Ismail, T. Bin, & Behlil, F. (2021). Prediction of heat waves over Pakistan using support vector machine algorithm in the context of climate change. *Stochastic Environmental Research and Risk Assessment*, 35(7), 1335–1353. <https://doi.org/10.1007/s00477-020-01963-1>
- Kamruzzaman, M., Rahman, A. T. M. S., Basak, A., Alam, J., & Das, J. (2023). Assessment and adaptation strategies of climate change through the prism of farmers' perception: A case study. *International Journal of Environmental Science and Technology*, 20(5), 5609–5628. [https://doi.org/10.1007/s13762-022-04254-Kipkemboi, B., Lalit, K., & Richard, K. \(2021\). Climate change and variability in Kenya : A review of impacts on agriculture and food security. *Environment, Development and Sustainability*, 23\(1\), 23–43. <https://doi.org/10.1007/s10668-020-00589-1>](https://doi.org/10.1007/s13762-022-04254-Kipkemboi, B., Lalit, K., & Richard, K. (2021). Climate change and variability in Kenya : A review of impacts on agriculture and food security. Environment, Development and Sustainability, 23(1), 23–43. https://doi.org/10.1007/s10668-020-00589-1)
- Kom, Z., Nethengwe, N. S., Mpandeli, N. S., & Chikoore, H. (2022). Determinants of small-scale farmers' choice and adaptive strategies in response to climatic shocks in Vhembe District, South Africa. *GeoJournal*, 87(2), 677–700. <https://doi.org/10.1007/s10708-020-10272-7>
- Kumar, M., Ratwan, P., Dahiya, S. P., & Nehra, A. K. (2021). Climate change and its impact on livestock production in India: A review. *Journal of Thermal Biology*, 97, 102867. <https://doi.org/10.1016/j.jtherbio.2021.102867>
- Lopez, R. A., Laughton, C., Kim, D., & Suh, H. S. (2022). *Climate change and productivity of northeastern dairy farms*. *Applied Economic Perspectives and Policy*, 44(1), 203–221. <https://doi.org/10.1017/age.2022.2>
- Malhi, G. S., Kaur, M., & Kaushik, P. (2021). Impact of climate change on agriculture and its mitigation strategies: A review. *Sustainability*, 13(3), 21. <https://doi.org/10.3390/su13031318>
- Mbuthia, J. M., Eggert, A., & Reinsch, N. (2022). Cooling temperature humidity index-days as a heat load indicator for milk production traits. *Frontiers in Animal Science*, 3, 1–9. <https://doi.org/10.3389/fanim.2022.946592>

- Martel, J. C. F., Brown, M. T. H. J. N., & Smith, R. R. A. P. (2021). Negative relationship between dry matter intake and the temperature - humidity index with increasing heat stress in cattle : a global meta - analysis. *International Journal of Biometeorology*, 65(11), 2099–2109. <https://doi.org/10.1007/s00484-021-02167-0>
- Mehmood, U., Tariq, S., Ul-Haq, Z., & Meo, M. S. (2022). Does the modifying role of institutional quality remains homogeneous in GDP-CO2 emission nexus? New evidence from ARDL approach. *Environmental Science and Pollution Research*, 29(8), 11817–11825. <https://doi.org/10.1007/s11356-021-16533-3>
- Mirzabaev, A., Bezner, R., Hasegawa, T., Pradhan, P., Wreford, A., Cristina, M., Pahlen, T. Von Der, & Gurney-smith, H. (2023). Climate Risk Management Severe climate change risks to food security and nutrition. *Climate Risk Management*, 39, 100473. <https://doi.org/10.1016/j.crm.2022.100473>
- Montcho, M., Padonou, E. A., & Montcho, M. (2022). Perception and adaptation strategies of dairy farmers towards climate variability and change in West Africa. *Scientific African*, 16, e01167. <https://doi.org/10.1016/j.sciaf.2022.e01167>
- Moore, S. S., Costa, A., Penasa, M., Callegaro, S., & De Marchi, M. (2023). How heat stress conditions affect milk yield, composition, and price in Italian Holstein herds. *Journal of Dairy Science*, 106(6), 4042–4058. <https://doi.org/10.3168/jds.2022-22640>
- Mehmood Ul, H., Tassaduq, H., Chandni, R., Adnan, I., & Muhammad, A. (2022). Linking Plants Functioning to Adaptive Responses Under Heat Stress Conditions : A Mechanistic Review The Intergovernmental Panel on Climate Change. *Journal of Plant Growth Regulation*, 41(7), 2596–2613. <https://doi.org/10.1007/s00344-021-10493-1>
- Muluneh, M. G. (2021). Impact of climate change on biodiversity and food security: a global perspective — a review article. *Agriculture & Food Security*, 10(1), 1–25. <https://doi.org/10.1186/s40066-021-00318-5>
- Murshed M, Nurmakhanova M, Al-Tal R, Mahmood H, Elheddad M, Ahmed R (2022). Can intra-regional trade, renewable energy use, foreign direct investments and economic growth reduce ecological footprints in South Asia? *Energy Sources, Part B: Economics, Planning, and Policy*, 17(1), 2038730. <https://doi.org/10.1080/15567249.2022.2038730>
- Neethirajan, S. (2024). Innovative Strategies for Sustainable Dairy Farming in Canada amidst Climate Change. *Sustainability* 16(1), 265. <https://doi.org/10.3390/su16010265>
- Osei-Amponsah, R., Dunshea, F. R., Leury, B. J., Cheng, L., Cullen, B., Joy, A., Abhijith, A., Zhang, M. H., & Chauhan, S. S. (2020). Heat stress impacts on lactating cows grazing australian summer pastures on an automatic robotic dairy. *Animals*, 10(5), 869. <https://doi.org/10.3390/ani10050869>
- Ouyang, H., Tang, X., & Zhang, R. (2022). Research Themes, Trends and Future Priorities in the Field of Climate Change and Health: A Review. *Atmosphere*, 13(12),2076. <https://doi.org/10.3390/atmos13122076>
- Ozdemir , D., Özkan, B., & Özçelik, A. (2022). The impact of climate change on agricultural productivity in Asian countries: A heterogeneous panel data approach. *Environmental Science and Pollution Research*, 29(6), 8205–8217. <https://doi.org/10.1007/s11356-021-16291-2>
- Park, G.W., Ataallahi, M., Ham, S.Y., Oh, S.J., Kim, K.Y& Park, K.H.,(2022). Estimating milk production losses by heat stress and its impacts on greenhouse gas emissions in Korean dairy farms. *Journal of Animal Science and Technology*, 64(4), 770-782.<https://ssrn.com/abstract=4701129>

- Rahimi, J., Mutua, J. Y., Notenbaert, A. M. O., Dieng, D., & Butterbach-Bahl, K. (2020). Will dairy cattle production in West Africa be challenged by heat stress in the future? *Climatic Change*, 161(4), 665–685. <https://doi.org/10.1007/s10584-020-02733-2>
- Rana, I. A., Sikander, L., Khalid, Z., Nawaz, A., Najam, F. A., Khan, S. U., & Aslam, A. (2022). A localized index-based approach to assess heatwave vulnerability and climate change adaptation strategies: A case study of formal and informal settlements of Lahore, Pakistan. *Environmental Impact Assessment Review*, 96, 106820. <https://doi.org/10.1016/j.eiar.2022.106820>
- Rodriguez-Venegas, R., Meza-Herrera, C. A., Robles-Trillo, P. A., Angel-Garcia, O., Legarreta-Gonzalez, M. A., Sánchez-Vocanegra, H. F., & Rodriguez-Martinez, R. (2023). Effect of THI on Milk Production, Percentage of Milking Cows, and Time Lying in Holstein Cows in Northern-Arid Mexico. *Animals*, 13(10), 1–14. <https://doi.org/10.3390/ani13101715>
- Romanello, M., Di Napoli, C., Drummond, P., Green, C., Kennard, H., Lampard, P., Scamman, D., Arnell, N., Ayeb-Karlsson, S., Ford, L. B., Belesova, K., Bowen, K., Cai, W., Callaghan, M., Campbell-Lendrum, D., Chambers, J., van Daalen, K. R., Dalin, C., . . . Costello, A. (2022). The 2022 report of the Lancet Countdown on health and climate change: Health at the mercy of fossil fuels. *The Lancet*, 400(10363), 1619–1654. [https://doi.org/10.1016/S0140-6736\(22\)01540-9](https://doi.org/10.1016/S0140-6736(22)01540-9)
- Ranjitkar, S., Bu, D., Van Wijk, M., Ma, Y., Ma, L., Zhao, L., Shi, J., Liu, C., & Xu, J. (2020). Will heat stress take its toll on milk production in China? *Climatic Change*, 161(4), 637–652. <https://doi.org/10.1007/s10584-020-02688-4>
- Roy, P. S., Ramachandran, R. M., Paul, O., Thakur, P. K., Ravan, S., Dev, M., Chandan, B., & Vijay, S. (2022). Anthropogenic Land Use and Land Cover Changes — A Review on Its Environmental Consequences and Climate Change. *Journal of the Indian Society of Remote Sensing*, 50(8), 1615–1640. <https://doi.org/10.1007/s12524-022-01569-w>
- Shafiq, M. N., Gillani, S., & Shafiq, S. (2021). Climate Change and Agricultural Production in Pakistan. *IRASD Journal of Energy & Environment*, 2(2), 47–54. <https://doi.org/10.52131/jee.2021.0202.0016>
- Shahbaz, P., Boz, I., & ul Haq, S. (2020). Adaptation options for small livestock farmers having large ruminants (cattle and buffalo) against climate change in Central Punjab Pakistan. *Environmental Science and Pollution Research*, 27(15), 17935–17948. <https://doi.org/10.1007/s11356-020-08112-9>
- Shantharaju, A., Islam, A., Kath, J. M., Mushtaq, S., Muniyappa, A., & Singh-peterson, L. (2024). *Understanding Constraints and Enablers of Climate Risk Management Strategies : Evidence from Smallholder Dairy Farmers in Regional South India*. *Climate Risk Management*, 43, 100588. <https://doi.org/10.1016/j.crm.2023.100588>
- Sharma, A., & Andhikaputra, G. (2022). *Heatwaves in South Asia : Characterization , Consequences on Human Health , and Adaptation Strategies*. *Atmosphere*, 13(5), 734. <https://doi.org/10.3390/atmos13050734>
- Slimen, I. B., Najar, T., Ghram, A., & Abdrrabba, M. (2020). *Heat stress effects on livestock : molecular , cellular and metabolic aspects , a review*. *Journal of Animal Physiology and Animal Nutrition*, 100(3), 401–412. <https://doi.org/10.1111/jpn.12379>
- Theusme, C., Avendaño-Reyes, L., Macías-Cruz, U., Correa-Calderón, A., García-Cueto, R. O., Mellado, M., Vargas-Villamil, L., & Vicente-Pérez, A. (2021). Climate change vulnerability of confined livestock systems predicted using bioclimatic indexes in an

- arid region of México. *Science of the Total Environment*, 751, 141779. <https://doi.org/10.1016/j.scitotenv.2020.141779>
- Thornton, P., Nelson, G., Mayberry, D., & Herrero, M. (2022). Impacts of heat stress on global cattle production during the 21st century: a modelling study. *The Lancet Planetary Health*, 6(3), e192–e201. [https://doi.org/10.1016/S2542-5196\(22\)00002-X](https://doi.org/10.1016/S2542-5196(22)00002-X)
- Tofu, D. A., Haile, F., & Tolossa, T. (2023). Livelihood vulnerability and socio-economic determinants of households to climate change-induced recurrent drought in Ethiopia. *GeoJournal*, 88(5), 5043– 5067. <https://doi.org/10.1007/s10708-023-10904-8>
- Ullah, S., You, Q., Chen, D., Sachindra, D. A., AghaKouchak, A., Kang, S., Li, M., Zhai, P., & Ullah, W. (2022). Future population exposure to daytime and nighttime heat waves in South Asia. *Earth's Future*, 10(5), e2021EF002511. <https://doi.org/10.1029/2021EF002511>
- Ullah, F., Valente, M., Hubloue, I., Akbar, M. S., Ragazzoni, L., & Barone-Adesi, F. (2024). Determinants of adaptive behaviors during heat waves in Pakistan: A study based on personal heat wave experiences and hypothetical scenarios. *Mitigation and Adaptation Strategies for Global Change*, 29(5), 55. <https://doi.org/10.1007/s11027-024-10144-2>
- United Nations, Department of Economic and Social Affairs, Population Division. (2024). *World population prospects 2024: Summary of results* (Report No. UN DESA/POP/2024/TR/NO. 4). United Nations.
- Usman M, Balsalobre-Lorente D, Jahanger A, Ahmad P (2022). Pollution concern during globalization mode in financially resource rich countries: Do financial development, natural resources and renewable energy consumption matter? *Renewable Energy* 183(1), 90–102 <https://doi.org/10.1016/j.renene.2021.10.067>
- Volk, G. M., Moreau, T. L., & Byrne, P. F. (2023). Climate change impacts agricultural productivity and food security. In V. A. Lombard, M. B. Kantar, & C. R. Richards (Eds.), *Conserving and using climate-ready plant collections* (pp. 1–12). Burleigh Dodds Science Publishing. <https://doi.org/10.19103/as.2023.0121.01>
- Wagoner, R. S., Nicolas, I. L., De Zapien, J. G., Grinshpun, S. A., Canales, R. A., & Beamer, P. I. (2020). An occupational heat stress and hydration assessment of agricultural workers in North Mexico. *International Journal of Environmental Research and Public Health*, 17(6), 2102. <https://doi.org/10.3390/ijerph17062102>
- Wankar, A. K., Rindhe, S. N., & Doijad, N. S. (2021). Heat stress in dairy animals and current milk production trends, economics, and future perspectives: the global scenario. *Tropical Animal Health and Production*, 53(1), 709. <https://doi.org/10.1007/s11250-020-02541-x>
- Yan, G., Li, H., & Shi, Z. (2021). Evaluation of thermal indices as the indicators of heat stress in dairy cows in a temperate climate. *Animals*, 11(8), 2459. <https://doi.org/10.3390/ani11082459>