# PHENOTYPIC PLASTICITY IN TOGGENBURG DAIRY GOATS ON MILK PRODUCTION TRAITS ACROSS AGRO-ECOLOGICAL ZONES OF SOUTH AFRICA

by

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## DECLARATION

I, TSHEPHO MATSHEBUKA, declare that this research report hereby submitted to the University of Limpopo for the degree of Master of Science in Agriculture (Animal Production) has not been submitted by me for a degree at this or any other university, this is my own work in design and execution, and that all materials contained herein has been duly acknowledged. The research was approved by the University of Limpopo Animal Research Ethics Committee (Registration no. AREC-290914-017) (Appendix A).

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## DEDICATION

This work is dedicated to my parents; Anna Mmalehu Matshebuka and Andries Ngako (MAY HIS SOUL REST IN ETERNAL PEACE), my siblings (Lebo and Dineo) who were always in support of me in my journey.

## ABSTRACT

Toggenburg dairy goats, which are valued for their versatility and excellent milk production under a variety of environmental conditions, are essential to the South African dairy industry. The aim of this study was to evaluate the phenotypic plasticity of the Toggenburg goat breed in milk production in South Africa's various agroecological zones (AEZ). Performance records of 2417 does born from 1955-2018 across five agro-ecological zones with five differing breed purity levels were obtained from the Milch Breeders Society of South Africa LOGIX database. Pedigree data and reproductive indices were included with the performance data. Descriptive statistics of milk production, reproductive, and dairy value traits computed using General Linear Model of Minitab 18.1 software. Significant animal and environmental factors affecting productivity were determined using ANOVA. Four methods of determining the phenotypic plasticity index (PPI) were compared. These were reaction norm-based, infinite-dimensional model, character trait, and variance-based model. The p-value and $R^2$ values were used to assess the significance of the estimates and goodness-of-fit. Data visualisation techniques used included surface plots and phenotypic plasticity trends. The results showed that the winter kidding season showed high kid status (0.6269±0.0820 healthy) $(p<0.05)$, while spring showed the highest somatic cell count (SCC) (302±103 cells/ml). AEZs significantly $(p<0.05)$ influenced the arid zone to produce the largest litter size (2.069±0.113 kids) and the temperate zone produced the highest lactation milk yield (647.32±5.59 kg). Blood breed purity levels showed a significant effect $(p<0.05)$, with a high lactation milk yield in Founders (675.1±17.9 kg). Litter size was affected by dam parity ($p<0.05$), with a higher number of kids at parities 2 (1.9464±0.0984 %), 3 (1.947±0.100 %), 4 (2.052±0.108 %), 5 (1.958±0.115 %), and 7 (2.183±0.164 %). At parity 10 better milk persistency (81.54±8.18 %) was observed. Variance-based and character trait methods revealed significant phenotypic plasticity $(p<0.05)$ in somatic cell count, kid status score, litter size, and ease score in high humidity and low temperature zone. Reaction norm analysis also demonstrated significant plasticity $(p<0.05)$ in kid status score, birth difficulty score, Milk Urea Nitrogen, milk persistency, lactation value index, lactose with $R^2$ of 81.58% milk yield exhibiting a high $R^2$ of 99.64% among the F0 purity levels. Regression model analysis confirmed significant ($p<0.05$) genotype-by-environment (GxE) interactions ($p<0.05$) for lactose with $R^2$ of 81.58%, dam longevity (r = 82.57%), milk persistence, birth difficulty score, and kidding ease score. PPI was not significant ($p>0.05$) across genotypes and AEZ in key AFK and KI in all methods. Surface plots and phenotypic plasticity trends confirmed the observed results in all traits, with lactation milk yield, prolificacy (litter size), and dam longevity indicating conspicuous phenotypic plasticity. The study concludes that the evaluated fixed factors have a significant impact on Toggenburg goat reproductive performance, milk production traits, and dairy value traits. Therefore, Toggenburg goat blood purity levels exhibit phenotypic plasticity, showing their ability to adapt to changing environmental conditions in the various agro-ecological zones of South Africa, revealing the reaction norm-based method as the most effective for assessing phenotypic plasticity.

**Key words:** Studbook, dairy value traits, breed purity levels, persistency, dam longevity

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| | |
|---|---|
| ADG | Average Daily Gain |
| AEZ | Agro-Ecological Zone |
| ANOVA | Analysis of Variance |
| AR | Arid |
| AREC | Animal Research Ethics Committee |
| AS | Animal Section |
| AVG | Average |
| BSTAT | Birth Status |
| BW | Birth Weight |
| BY | Birth Year |
| CEC | Cross-Environmental Correlation |
| DA | Dam Age |
| DAFF | Department of Agriculture, Fisheries and Forestry |
| DALRRD | Department of Agriculture, Land Reform and Rural Development |
| DL | Dam Longevity |
| DNA | Deoxyribonucleic Acid |
| DP | Dam Parity |
| DW | Dam Weight |
| F0 | Founder stock |
| FAO | Food and Agriculture Organization |
| FAOSTAT | Food and Agriculture Organization Statistics |
| GDP | Gross domestic product |
| GLM | General Linear Model |
| GXE | Genotype by Environment |
| HU | Humid |
| ID | Identity |
| KE | Kidding Ease |
| KS | Kid Status |
| LFY | Lactation Fat Yield |
| LHPG | Livestock Health and Production Group |

| | |
|---|---|
| LI | Lactation Index |
| LL | Lactation Length |
| LMY | Lactation Milk Yield |
| LOGIX | Livestock Operational and Genetic Information Exchange |
| LPY | Lactation Protein Yield |
| LS | Litter size |
| LSD | Least Significant Difference |
| LV | Lactation Value |
| LVI | Lactation Value Index |
| MP | Milk Persistency |
| MS | Microsoft |
| MUN | Milk Urea Nitrogen |
| PPI | Phenotypic plasticity index |
| SAMGBS | South African Milk Goat Breeders Society |
| SAR | Semi-Arid |
| SU | Semi humid |
| SCC | Somatic Cell Count |
| SE | Standard Error |
| SETA | Sector Education and Training Authority |
| SHU | Sub-Humid |
| SP | Stud Proper |
| TOG | Toggenburg goats |
| UL | University of Limpopo |
| WW | Weaning Weight |

| | |
|---|---|
| $\beta$ | Beta |
| °C | Degree Celsius |
| $\int$ | Integral |
| $\bar{x}$ | Mean for x values |
| $\bar{y}$ | Mean for y values |

# CHAPTER 1

## 1. INTRODUCTION

## 1.1. Problem statement

Goat milk became a more significant dairy product, with global production increasing from 12 million tons in 1993 to around 19 million tons in 2017 (Mehdid *et al.,* 2019). The production of 57% of the world's goat milk supply was in Asia, 24% in Africa, 15% in Europe and 4.4% in America. In Africa, goats play a key role in improving livelihoods and food security (Roets and Kirsten, 2017). Alpine, Toggenburg, Saanen, and Bunte Deutsche Edelzieged are dairy breeds recognised by the South African Milk Goat Breeders' Society (SAMGBS) (SA Milch Goat Breeders’ Society, 2025). Around 35 million goats are kept in southern Africa, the minority are kept in large-scale production systems in urban areas (Mataveia, Visser and Sitoe, 2021).

One of the main problems in commercial dairy goat farming is the lack of grazing pasture due to urbanisation and industrialisation (Lu and Miller, 2019). Most commercial dairy goat farms are expanding close to urban areas, yet there are obstacles there, such as endemic infections such as Brucella mellitensis and *Chlamydia spp*. or lack of laboratory services for disease diagnosis (Erduran and Dag, 2021). Due to daily increases in feed and feed costs, as well as increased demand for nutrients to produce milk, input costs are rising (Podhorecká *et al.,* 2021). On the other hand, dairy farmers who only use unimproved pastures frequently have low milk production because their animals' nutritional needs are not met, so in South Africa, goats do not produce a considerable amount of milk (Xue and Leibler, 2018). Extremely high rainfall and high relative humidity in South Africa, coldness in winter, heat waves in summer, and higher temperature affect the normal physiology and productivity of dairy goats (Bonamour *et al.,* 2019). One of the reasons for kid fatality is hypothermia, while dairy goats' ability to produce and reproduce is negatively impacted by hot temperatures (Roy and Patbandha, 2024). Farmers' ignorance of scientific rearing practices results in poor management, which lowers economic gains when it comes to milk production (Mokoena *et al.,* 2023). Therefore, with a wide spectrum of climatic conditions, the different agro-ecological zones are defined, which warrants an evaluation of phenotypic plasticity in milk production of particular dairy goat breeds farmed in South Africa.

## 1.2. Rationale

It has become vital to expand the contribution of dairy goats as a viable source of milk protein to address the difficulties of poverty and malnutrition in most rural parts of South Africa (Mokoena *et al.,* 2023). Humans need goat milk as part of a balanced diet because it is more easily absorbed than cow milk (Metzger, 2022). Although it has long been known to offer medicinal benefits, including antiallergic characteristics, milk provides protein, energy, minerals, and vitamins (Xue and Leibler, 2018). Goats require less care than cows, making them the perfect animal for farmers who want to produce milk across agro-ecological zone of South Africa (Mehdid *et al.,* 2019). Goat enterprises require less capital investment and carry fewer risks overall, which is another benefit of goat milk production (Kaskous *et al*., 2020). Most rural people rely on indigenous goats for meat and milk, despite the fact that these animals have never traditionally been chosen for their ability to produce either (Podhorecká *et al.,* 2021).

Typically, dairy goats are believed to produce enough milk to feed their young and have extra for human use (Erduran and Dag, 2021). However, it turns out that they cannot produce enough for both young and the fulfillment of human demands because they were never chosen for their ability to produce such amounts of milk (Norris *et al.,* 2011). There are many breeds of dairy goats (Toggenburg, Saanen, Bunte Deutsche Edelzieged, and Alpine) that have been bred to produce more milk, but their performance under South African conditions has not been sufficiently explored. These breeds could be used as substitute milk producers in rural South African areas, it was highlighted in the paper by Norris *et al.,* (2011) that important factors that affect milk composition and quality include nutritional value and consumer attractiveness. Many studies (Morand-Fehr and Sauvant, 1980; Greyling *et al.,* 2004) have also examined the impact of nutrition and management on milk production, but few have addressed aspects such as lactation stage, parity, breed, and season, which have been proven to have an impact on milk composition (Norris *et al.,* 2011). Furthermore, the effect of agro-ecological zones in South Africa on goat milk production has not been addressed. Also, the lack of knowledge on how plastic is the phenotypic traits of Toggenburg goats which necessitated the carrying out of this research. Therefore, the study aimed at assessing phenotypic plasticity in milk production of Toggenburg goat breed across different agro-ecological zones of South Africa.

## 1.3. Objectives

Specific objectives of the study were:

1. To determine environmental factors affecting milk production of Toggenburg goat in South Africa.
2. To determine animal factors affecting milk production of Toggenburg goat in South Africa.
3. To determine phenotypic plasticity of Toggenburg goat blood purity levels across agro-ecological zones of South Africa.

## 1.4. Hypothesis

The null hypotheses of the study were:

1. Kidding season, agro-ecological zone, lactation length, and birth year do not affect milk urea nitrogen, protein, lactose, persistency, somatic cell count, and lactation milk yield of Toggenburg dairy goat in South Africa.
2. Dam parity, litter size, and kid sex genotype, and animal birth status do not affect milk urea nitrogen, protein, lactose, persistency, somatic cell count, and lactation milk yield of Toggenburg goat in South Africa.
3. There is no phenotypic plasticity in milk production of stud Toggenburg dairy goat genotypes across agro-ecological zone of South Africa.

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# CHAPTER 2

# LITERATURE REVIEW

## 2.1 Introduction

This section of the mini-dissertation comprehensively explored Toggenburg dairy goats in South Africa, with a specific focus on milk production traits across diverse agro-ecological zones. The examination encompasses critical dimensions, beginning with an in-depth analysis of the goat milk production industry in South Africa and shedding light on its significance, challenges, trends, and potential for growth. Subsequently, the adaptive characteristics of Toggenburg goats were scrutinised, delving into their genetic makeup and behavioural traits that enable survival under varied environmental conditions, setting the stage for discussions of their relationship with milk production. Furthermore, the productive characteristics of Toggenburg goats were explored, including aspects such as reproductive performance, growth rates, and other factors that directly influence milk production. The investigation expanded to the various factors that affect goat milk production in South Africa, encompassing environmental, genetic, animal-related, and husbandry factors. Moreover, the concept of phenotypic plasticity was elucidated, providing insights both adaptive and nonadaptive plasticity. Finally, different methods of measuring phenotypic plasticity, such as reaction norms, Common Garden experiments, cross-environmental correlations, heritability estimates, and manipulative experiments, as well as methods of calculating phenotypic plasticity index, providing a comprehensive understanding of the subject matter.

## 2.2 Goat milk production in South Africa

Goat milk production in South Africa is shaped by the substantial goat population, which comprises approximately 55% of the total goat population in Southern Africa (FAOSTAT, 2020). The main provinces that contribute to this population include the Eastern Cape (32%), Limpopo (14%), KwaZulu-Natal (11%), Northern Cape (7%), Western Cape (3%), Free State (3%), Mpumalanga (1%), Gauteng (2%) and Northwest (10%), accounting for 83% of goats in the country (DAFF, 2012/13). Although the total goat population in South Africa has gradually declined at an annual rate of 1.77%, the number of goats designated for milk production has increased, particularly in the western and eastern regions (Kahi and Wasike, 2019). Dairy goat breeds in the country consist mainly of imported Saanen, Toggenburg, and Alpine breeds, which are managed along with cattle in the national Dairy Animal Improvement

Scheme (Mohlatlole *et al.,* 2015). However, the limited availability of official goat milk production data is due to the integration of goat milk records with those of dairy cattle and the lack of record keeping by subsistence farmers (Mohlatlole *et al.,* 2015).

Despite data limitations, the dairy goat sector in South Africa has experienced growing demand, particularly due to the growing interest in goat milk products for people with dietary and health needs (Escareño *et al.,* 2012). However, maintaining a consistent milk supply remains a challenge due to seasonal breeding and adaptability issues of dairy goats in diverse production environments (Mohlatlole *et al.,* 2015). Furthermore, disease challenges, particularly heartwater, have affected goat production throughout the country, with higher occurrences in summer rainfall areas (DAFF, 2012; LHPG, 2013, 2014). On the economic front, livestock production, including goat milk, has contributed significantly to South Africa's agricultural GDP, making up between 40% and 50% of the total agricultural output (Erdaw, 2023). With increasing goat milk production, the country has been able to increase its exports, particularly to neighbouring countries such as Namibia and Botswana, while also importing speciality goat milk products such as cheese and yoghurt from European nations to meet local consumer preferences (DAFF, 2022; FAO, 2023).

South Africa's diverse agro-ecological zones influence goat milk production, with higher yields observed in temperate and high rainfall regions such as the Western Cape and KwaZulu-Natal, where favourable climatic conditions support better forage availability (Faye *et al.,* 2017). On the contrary, arid and semi-arid areas such as Karoo experience lower milk production due to limited pasture and water resources, leading to seasonal variations in milk production (Moholo *et al.,* 2018; Nurfeta *et al.,* 2016). The adaptation of breeds to different regions also plays a role in production levels, with indigenous breeds like Nguni and Boer thriving in traditional smallholder systems in harsher climates, while specialised dairy breeds such as Saanen and Toggenburg dominate commercial dairy operations in more favourable agro-ecological zones (Tesema *et al.,* 2020; Moholo *et al.,* 2018). Intensive management practices, including improved housing, nutrition, and healthcare, are commonly employed in commercial enterprises to maximise milk production efficiency, further highlighting the impact of environmental and management factors on the production of dairy goats in South Africa (Nurfeta *et al.,* 2016).

## 2.3 Adaptive characteristics of Toggenburg goats in South Africa.

Goats play a crucial role in South African livestock production due to their resilience to climate change, ability to thrive on limited resources, and their resistance to diseases (Nair *et al.,* 2021). Their adaptability to harsh environments makes them particularly valuable in arid and semi-arid regions, where climate change increases agricultural uncertainty (Monau *et al.,* 2020). Herders recognise that goats are more resilient than sheep and cattle, particularly when dealing with water and feed scarcity, heat stress, and poor-quality vegetation (Mergasa *et al.,* 2014). However, while goats are well adapted to tropical climates, high temperatures can still negatively impact milk production, reducing yields by 3% to 10% (Sejian *et al.,* 2021). Under heat stress, goats rely on various physiological and biochemical responses to regulate body temperature, but these adaptations divert energy away from production, prioritising survival over milk yield (Aleena *et al.,* 2018).

Genetic factors play an important role in determining the ability of goats to withstand environmental challenges (Silanikove and Koluman, 2015). Research on biomarkers for heat stress has facilitated selective breeding strategies aimed at improving disease resistance and overall resilience (Madhusoodan *et al.,* 2019; Aleena *et al.,* 2018). For example, studies emphasise the importance of selecting goats with genetic markers linked to strong immune responses and resistance to infections (Khraim *et al.,* 2020). Advances in genomic selection allow breeders to improve traits related to immune function, disease resistance, and mastitis resilience in Toggenburg goats (Kutzler *et al.,* 2018; Smith *et al.,* 2019; Salinas *et al.,* 2021). These breeding initiatives ensure that goats maintain productivity while adapting to the climatic challenges of the diverse agro-ecological zones of South African.

The genetic makeup of South African Toggenburg goats reflects both imported and indigenous traits, with selective breeding programs that improve milk production, reproductive performance, and environmental adaptability (Bosman, 2015; Zhang *et al.,* 2021). Toggenburg goats display behavioural adaptations suited to different management systems, including browsing behaviours in traditional smallholder settings and more docile temperaments in intensive dairy operations (Dzomba *et al.,* 2017; Abegaz *et al.,* 2018). These adaptations highlight their ability to thrive in both extensive and intensive farming systems, ensuring their continued role in South African dairy production.

### 2.4 Productive characteristics of Toggenburg goats in South Africa.

Kidding success plays a vital role in goat milk production, as kid mortality reduces herd productivity by limiting the availability of replacement females (Upadhyay *et al.,* 2015; Kraai *et al.,* 2022). Larger herd sizes can also negatively affect offspring growth and weaning rates, particularly in challenging environmental conditions (Borries *et al.,* 2008). Seasonal and density-related stressors further influence reproductive performance, potentially impacting food security at the household and community levels (Kraai *et al.,* 2022). Although tropical goat breeds are known for their adaptability, their lower milk yields have led to the introduction of temperate breeds like Saanen and Toggenburg to improve productivity (Gore *et al.,* 2020). Although Saanen goats are often considered superior in milk production, Toggenburg goats have demonstrated better adaptation to semi-intensive tropical environments, highlighting the need for more comparative research on their reproductive and milk yield performance (Takahashi, 2011).

Toggenburg goat productivity is largely influenced by milk production, which directly affects profitability (Ahlawat *et al.,* 2020). The composition of goat milk, particularly its fat and protein content, significantly impacts its market value and nutritional quality (Lima *et al.,* 2021). Consumer demand for health-enhancing dairy products, such as those enriched with omega-3 fatty acids, further underscores the importance of selective breeding for desirable milk traits (Ribeiro *et al.,* 2020; Wang *et al.,* 2020). Reproductive traits such as kidding and twinning rates also contribute to herd productivity, with genetic selection playing a crucial role in improving these traits (Pauszek *et al.,* 2020). Reducing kidding intervals through selective breeding enhances reproductive efficiency, while effective management and disease control strategies help mitigate mortality rates, which can otherwise lead to financial losses and reduced productivity (Biscarini *et al.,* 2020; Bodzsár *et al.,* 2020; Gunawan *et al.,* 2021).

Growth traits significantly impact milk production in Toggenburg dairy goats, with birth weight (BW) and weaning weight (WW) serving as early indicators of milk production potential (Ferraz *et al.,* 2018; Gourdine *et al.,* 2018). Breeding weight also correlates with milk yield, as heavier animals typically produce more milk due to their enhanced metabolic capacity (Nguyen *et al.,* 2020). Similarly, average daily gain (ADG) influences lactation performance by determining body reserves and nutrient efficiency (Bertolini et al., 2019; Sejian *et al.,* 2019). Furthermore, reproductive factors such as age at first kidding, kidding intervals, and longevity affect the overall milk production potential of a herd (Abegaz *et al.,* 2018; Mavrogenis *et al.,* 2019; Tesema *et al.,* 2020). Effective management of these traits ensures consistent milk production, with lower mortality rates contributing to a stable and productive milking herd (Tesema *et al.,* 2017; Ndiweni *et al.,* 2018; Shongwe *et al.,* 2021).

## 2.5 Factors affecting goat milk production in South Africa.

### 2.5.1 Animal factors

Various breeds of goats are raised in diverse production environments worldwide. However, observations in one specific setting may not universally apply to others (Goetsch *et al.,* 2011). Research typically emphasises the breeds of dairy goats selected for their milk production in terms of yield and quality. However, the physiological state during lactation is crucial for all goat genotypes and significantly impacts the food and economic well-being of millions of people (Goetsch *et al.,* 2011).

Age is a key factor influencing goat milk production, with variations evident in different stages of life. In the early stages of lactation, younger goats exhibit enhanced mammary gland development, leading to increased milk production (Smith *et al.,* 2018). As goats age, a decrease in milk production becomes pronounced due to factors such as reduced glandular tissue and hormonal fluctuations associated with ageing (Yu *et al.,* 2020; Smith *et al.,* 2018). Research by Yu *et al.* (2020) specifically highlights a significant decrease in milk production with advancing age in Saanen goats. Furthermore, the metabolic efficiency of older goats can decrease, adversely affecting their ability to convert nutrients into milk (Gebreyowhans *et al.,* 2016; Smith *et al.,* 2018; Salama *et al.,* 2018). To optimise goat productivity throughout its lifespan, it is essential to implement strategic management practices, nutritional interventions, and breeding strategies, as emphasised by various studies (Gebreyowhans *et al.,* 2016; Salama *et al.,* 2018; Smith *et al.,* 2018).

The health status of goats plays a vital role in influencing milk production, as several interconnected factors contribute to the general well-being of animals. The research by Salama *et al.* (2018) underscores that healthy goats are more likely to exhibit higher milk yields. Disease susceptibility, including infections or parasitic infestations, can negatively impact milk production by compromising the physiological functions of goats (Hagos *et al.,* 2016). Additionally, nutritional deficiencies resulting from poor health can lead to suboptimal levels of milk production (Silanikove *et al.,* 2010). The importance of proactive health management is evident in its direct correlation with both milk quality and quantity.

### 2.5.2 Genetic factors

Genetic factors play a crucial role in determining goat milk production, with certain breeds showing varying potentials for milk production. Amills *et al.* (2017) highlighted that genetic traits associated with mammary gland development and lactation physiology significantly enhance milk production. Selective breeding programs targeting these traits have led to substantial improvements in overall milk production. The study on Saanen goats by Yu *et al.* (2020) further reinforced this notion, showing that specific breeds are genetically inclined toward higher milk production levels. Furthermore, genetic variation within a breed also contributes to differences in individual milk yields, emphasising the importance of genetic selection (Smith *et al.,* 2018).

The genetic composition of Toggenburg goats influences their milk production performance, with hereditary factors shaping milk yield and composition (Visser, 2018). Toggenburg goats are genetically predisposed to moderate to high milk productions, with lactation persistency being a key trait that supports consistent production over time (Zindove *et al.,* 2023). Selective breeding has improved traits such as udder health, milk production, and milk composition, contributing to improved productivity (Hlophe *et al.,* 2020). However, genetic diversity within Toggenburg populations also affects milk production, as variations in individual genetic makeup lead to differences in milk production (Zindove *et al.,* 2023). Furthermore, environmental conditions interact with genetic factors, influencing overall production results and highlighting the need for breeding programs that consider both genetic and environmental adaptability (Hlophe *et al.,* 2020).

Reproductive traits, including prolificacy and kidding intervals, significantly impact dairy goat milk production. Memzies *et al.* (2022) found that prolific goats with larger litter sizes often produce higher milk yields due to increased nutritional demands. Similarly, Ribeiro *et al.* (2019) and Muchenjie *et al.* (2019) linked prolificacy to enhanced reproductive efficiency, which in turn influences milk production in multiple lactation cycles. Improved reproductive efficiency, characterised by shorter kidding intervals and increased lifetime lactations, has been associated with higher cumulative milk yields (Salama *et al.,* 2018). Additionally, the heritability values of milk production traits provide information on the genetic potential for improvement, with highly heritable traits such as milk production being prime candidates for selective breeding (Visser, 2018; Gizaw *et al.,* 2019). To optimise productivity, breeding strategies should integrate genetic selection with environmental management practices, ensuring sustainable improvements in dairy goat milk production (Hlophe *et al.,* 2020).

### 2.5.3 Environmental factors

Climate and temperature significantly influence goat milk production, with recent studies highlighting the multifaceted impact of environmental conditions (Nascimento *et al.,* 2020; Salama *et al.,* 2018). High temperatures, characteristic of heat stress, are consistently associated with reduced milk production in dairy goats (Nascimento *et al.,* 2020). Heat stress leads to decreased feed intake, altered metabolism, and physiological stress, all contributing to a decrease in milk production (Pragna *et al.,* 2018). Adequate environmental management, such as providing shade and implementing cooling strategies, is crucial during periods of heat stress to mitigate its effects on milk production (Gantner *et al.,* 2021; Tao *et al.,* 2014). Morera *et al.* (2012) found that heat stress negatively impacts mammary gland functioning, affecting milk composition and quality. Integrating climate resilience strategies and considering temperature fluctuations are therefore imperative for sustainable milk production in goat farming systems (Huang *et al.,* 2021).

High humidity can exacerbate the adverse effects of heat stress on dairy goats, further compromising milk production due to reduced feed intake and increased physiological stress (Desta *et al.,* 2019). Furthermore, goats demonstrate resilience and adaptive advantages over sheep in mitigating the effects of heat stress, rooted in their unique physiological, morphological and behavioural adaptations (Ben-moula *et al.,* 2024). Forage quality also plays a central role; Gebreyowhans *et al.* (2016) highlighted that inadequate or poor quality forage can lead to nutritional deficiencies, affecting milk production in goats. Ensuring access to high-quality forage positively correlates with improved milk yield (Alves *et al.,* 2020).

### 2.5.4 Husbandry practices

Milking management practices, parasite control, and feeding strategies significantly influence goat milk production. Silva *et al.* (2020) emphasised the importance of milking hygiene and frequency, with proper udder stimulation, sanitation, and complete milk removal positively affecting milk production (Gökdai *et al.,* 2020). Effective parasite control is crucial, as parasitic infections can lead to reduced feed intake and compromised nutrient utilisation, thus negatively impacting milk yield (Brito *et al.,* 2017). Gebreyowhans *et al.* (2016) underscored the importance of feeding practices, stressing that access to quality forage, supplemented with concentrates to balance nutrition, is essential to optimise milk production in goats.

Implementing precise reproductive management practices, including synchronisation of oestrus cycles and timely breeding, contributes to a consistent and efficient production schedule (Akinsola *et al.,* 2021; Lopes *et al.,* 2019). This ensures that a higher percentage of goats within the herd are lactating at any given time, positively influencing overall milk yield (Dairy Goat Production, 2022). Moreover, strategic breeding programs that emphasise the selection of high-yielding dairy goat breeds and genetic improvement significantly contribute to enhanced milk production potential (Bhatta *et al.,* 2019). Safiullah *et al.* (2017) emphasised that controlled breeding schedules and genetic selection for desirable traits, such as increased lactation duration and higher milk yield, result in more productive and economically viable dairy goat enterprises (Rovuga and Maleko, 2023). Integrating reproductive and breeding practices improves the overall reproductive efficiency and genetic potential of the herd, promoting sustained milk production over successive lactation cycles (Santos *et al.,* 2018). Time, labour, and management are key factors in the success of the operation.

## 2.6 The concept of phenotypic plasticity.

Phenotypic plasticity has been defined differently due to applicability in different fields of biodiversity to understand the common ground in all. This section looks at the common concepts in livestock production, adaptive and nonadaptive plasticity, and methods of measuring phenotypic plasticity or types of phenotypic plasticity, especially in goats.

### 2.6.1 Definition of phenotypic plasticity.

Phenotypic plasticity in livestock refers to the capacity of an animal with a given genotype to exhibit a variety of traits in response to environmental changes (Whitman and Agrawal, 2009). This definition is consistent with those presented by Dewitt and Scheiner (2004), West-Eberhard (2003), and Freeman and Herron (2007). Furthermore, phenotypic plasticity can also refer to the phenomena in which a certain genetic composition results in distinct trait expressions in various environmental settings, as explained by Nayar (2014). Synonyms for this concept include phenotypic responsiveness, flexibility, and condition sensitivity, all of which highlight how adaptable livestock can be in their environment.

Unlike many other living species, livestock can exhibit a variety of morphological, physiological, or behavioural traits in response to their surroundings (Xue and Leibler, 2018). For example, cattle raised in different regions could exhibit distinct behaviours related to heat tolerance or variable coat thickness. Nayar (2014) noted that dietary differences can affect features such as muscle mass, milk production, and body size. Furthermore, as Freeman and Herron (2007) pointed out, management techniques including social interactions and housing arrangements can affect how a livestock's phenotypic expression is expressed.

### 2.6.2 Adaptive and non-adaptive plasticity.

The concepts of adaptive and nonadaptive phenotypic plasticity are fundamental to understanding how animals respond to environmental changes and the effects of these responses on their overall productivity and fitness. Adaptive plasticity refers to the ability of animals to modify their phenotypes in response to environmental stimuli, ultimately producing traits that enhance their chances of survival and reproduction. For example, some cattle breeds may exhibit adaptive plasticity in coat thickness in response to temperature fluctuations, helping them maintain optimal body temperature and prevent heat stress (Smith *et al.,* 2021). This adaptive response enhances their overall fitness and resilience under diverse environmental conditions.

In contrast, nonadaptive plasticity occurs when an animal's phenotypic changes do not enhance or may even diminish its fitness in a specific environment. Brown *et al.* (2020) noted that artificial lighting conditions can influence goat reproductive behaviours, similar to their effects on poultry farming. For instance, prolonged exposure to artificial lighting may alter a female goat's oestrus cycle or mating behaviours. Although these changes may initially appear to boost productivity, they can disrupt goats' normal reproductive cycles and induce physiological stress (Smith *et al.,* 2021). Consequently, this nonadaptive response to artificial lighting may adversely affect the overall health and productivity of the goat herd.

Research indicates that adaptive phenotypic plasticity is advantageous in situations involving slow-directional environmental changes and predictable fluctuations, such as variations in resource availability or temperature (Ghalambor *et al.,* 2015). Conversely, nonadaptive plasticity may result in phenotypic traits that deviate further from the local optimum, leading to increased directional selection pressures and a decline in relative fitness (Ghalambor *et al.,* 2015). Therefore, breeding strategies, management practices, and conservation initiatives must consider the mechanisms and implications of both adaptive and non-adaptive plasticity in livestock to enhance animal welfare and productivity across various environmental conditions.

## 2.7 Methods of measuring phenotypic plasticity.

There are several methods of ascertaining phenotypic plasticity which have been developed and published in science. These include the reaction norms method, common garden experiment, cross-environmental correlation, heritability estimates, manipulative experiments, and methods of calculating the phenotypic plasticity index (PPI). This section looks at these methods, explaining the procedures, their graphical presentations, and advantages and disadvantages.

### 2.7.1 Reaction norms

The reaction norm is defined more accurately as the phenotypic expression of a specific genotype for a single trait at varying levels of an environmental factor (Valladares *et al.,* 2014). This concept highlights how factors such as nutrition, environmental conditions, and management practices influence goat performance, including milk production and reproductive traits. For example, Ojango *et al.* (2020) demonstrated that variations in feeding schedules and environmental factors can significantly affect the milk yield of Toggenburg goats. By studying goat reaction norms, breeders can evaluate the adaptability and resilience of Toggenburg goats under diverse environmental conditions and management systems (Van der Waaij *et al.,* 2019). Similarly, Sonderman *et al.* (2021) emphasised the importance of incorporating reaction norms into breeding programs to develop genotypes that consistently perform well in a range of environments, ensuring long-term productivity and resilience in Toggenburg goat populations.

Reaction norm studies also provide valuable information on genotype-environment interactions, offering breeders a deeper understanding of the genetic potential of Toggenburg goats across different production systems. The research by Mrode *et al.* (2021) explored how various Toggenburg goat genotypes respond to climatic and management factors, revealing genetic heterogeneity in adaptive traits. Understanding reaction norms for traits such as heat tolerance or disease resistance is essential to develop breeding strategies that improve Toggenburg goat resilience in the face of changing climatic conditions (König *et al.,* 2020). Incorporating reaction norm data into breeding programs allows breeders to select genotypes that perform optimally under specific environmental conditions, thus improving overall productivity and sustainability in Toggenburg goat production systems (Gourdine *et al.,* 2020).).

The concept of reaction norms is well-established in evolutionary biology and has been widely applied in both theoretical and empirical studies of adaptive phenotypic plasticity. This approach extends to analysing behavioural and life history traits (Wright *et al.,* 2022). Applying the reaction norm framework to Toggenburg dairy goats aligns with West-Eberhard's (2008) assertion that environmental sensitivity often manifests as a continuous response. Studies such as those by Mrode *et al.* (2021) have examined milk production traits across different agro-ecological zones, assessing the effects of climate, forage availability, and management practices on milk yield in Toggenburg goats. However, it is important to note that reaction norms primarily describe traits with continuously varying responses and may not be suitable for traits governed by discrete or threshold-based mechanisms. For example, conditional alternative phenotypes in morphology or behaviour are better explained by threshold-based models rather than reaction norms.

The shape or curvature of reaction norms can vary-linear, quadratic, or monotonic, and the slope indicates the degree of phenotypic plasticity (Bhumika, 2023). The variation of the reaction norm can be analysed using various statistical techniques depending on its form and curvature (Morrissey and Liefting, 2016). Graphical representations are commonly used to visualise reaction norms, where the vertical axis represents the mean phenotypic value expressed by an individual under mean-centred environmental conditions. The slope of the reaction norm reflects the individual's responsiveness or extent of phenotypic change per unit of environmental variation (Wright *et al.,* 2022). For example, Figure 2.1 illustrates a typical reaction norm curve.

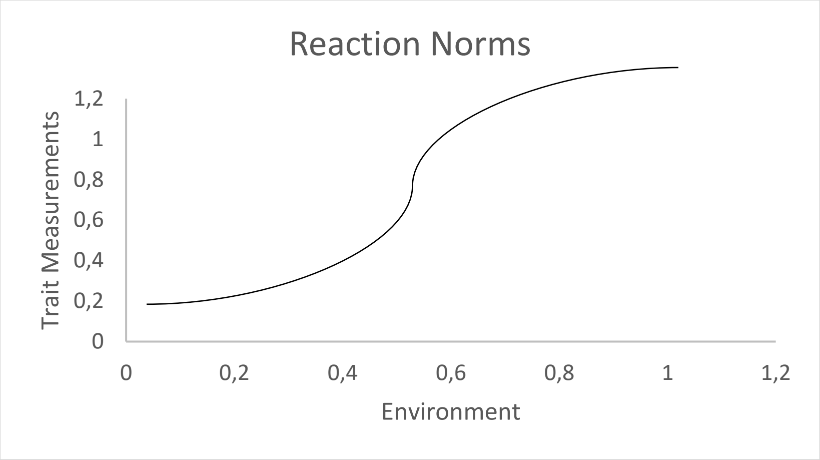

Figure 2.1 Reaction norm plot.

Reaction norm can be calculated using the following formula (Strand & Weisner, 2004).

VP = VG + VE + V GxE + V err

Where:

- VP is the phenotype expressed by an individual.
- VG represents the genotype of the organism.
- VE represents the environmental variable.
- V GxE describes the correlation between genotype and environment and how it influences the phenotype

- V err is the error term (representing any unexpected variation or noise in the observed phenotypic values)

### 2.7.1.1 Pros and Cons of reaction norm

According to Klinomos (2019), the reaction norm method provides a valuable framework to understand the complex relationship between environment and genotype that shapes the phenotypic variance. By viewing environmental sensitivity as a continuously fluctuating response, researchers can gain insight into an organism's capacity for adaptation across diverse habitats (Kremer *et al.,* 2017). This approach helps identify adaptive strategies and evolutionary mechanisms by examining how phenotypic traits, such as growth rates or reproductive behaviours, change along environmental gradients (Puentes *et al.,* 2021). Furthermore, reaction norms offer a quantifiable means of evaluating phenotypic plasticity, allowing scientists to measure the degree to which an organism modifies its phenotype in response to external stimuli (Barbour *et al.,* 2019). Furthermore, reaction norms improve our understanding of evolutionary processes such as local adaptation and speciation by clarifying the genotype-environment interactions that underlie phenotypic variation (Bouwhuis *et al.,* 2017). In general, the reaction norm method serves as an effective tool for examining the evolutionary and ecological dynamics of natural populations.

While reaction norms are useful, they also have limitations that must be considered. They can oversimplify the complexities of genotype-environment interactions, particularly in situations where environmental gradients are non-linear or multidimensional (Schneider *et al.,* 2020). Moreover, interpreting reaction norms can be challenging since phenotypic variation arises from a combination of environmental and genetic factors, along with their interactions (Thompson *et al.,* 2018). Additionally, because plastic responses can be context-dependent and influenced by factors such as developmental history and ecological context, reaction norms may not adequately represent the role of phenotypic plasticity in helping animals cope with environmental stressors (Stoks *et al.,* 2016). Furthermore, nonlinear or threshold-based responses may go unnoticed when assessing reaction norms using linear models, which could hinder our understanding of complex adaptive strategies (Dingemanse *et al.,* 2018).

To address these limitations, integrating theoretical models with empirical data can help clarify the factors influencing phenotypic variation in wild populations.

### 2.7.2 Common Garden experiment

Common garden experiments involve raising individuals from multiple populations under identical environmental conditions to assess the degree of adaptive genetic variation within those populations (de Villemereuil *et al.,* 2020). As noted by de Villemereuil *et al.* (2015), common garden experiments are used to test for local adaptation signals in traits such as life history traits (Kawakami *et al.,* 2011), phenology (Brachi et al., 2013), and allometric relationships (Gonda *et al.,* 2011). This approach allows researchers to uncover the genetic basis of complex phenotypes across various populations without the confounding effects of different environments (de Villemereuil *et al.,* 2015).

Local adaptation may be suspected when there are environmental gradients, such as latitude or altitude (Toräng *et al.,* 2015; Alberto *et al.,* 2011). Alternatively, it can be inferred from contrasting environments, such as sea and freshwater (DeFaveri and Merilä, 2013). Common garden experiments also serve as valuable tools to explore the implications of local adaptation for conservation efforts or ecosystem dynamics (Bassar *et al.,* 2010). However, the feasibility of this approach is constrained by the ability to rear the species and cultivate offspring under controlled laboratory or seminatural conditions. These experiments facilitate the examination of genotype-environment interactions, particularly when implemented across different environments (Villemereuil *et al.,* 2020). Despite logistical challenges, the insights gained from replicated common garden experiments are significant, given the prevalence and importance of genotype-environment effects in natural settings (Stinchcombe, 2014). Common garden experiments are often visually represented using box plots, which show the distribution of data for two or more groups (Kazakou *et al.,* 2013). Figure 2.2 illustrates the common garden.

**Figure 2.2** Common Garden experiments box plot.

### 2.7.2.1 Pros and Cons of Common Garden experiments

Common garden experiments provide a robust tool for elucidating the genetic basis of trait variation because they control environmental factors and standardise growth conditions between populations (Hereford, 2016). By cultivating individuals from different populations in a uniform environment, researchers can determine to what extent phenotypic differences between populations are attributable to genetic factors. This approach provides insight into the underlying genetic architecture of traits (Moran, 2019). Furthermore, common garden studies allow for the evaluation of phenotypic plasticity, since variations in trait expression among populations in a common environment can be ascribed to genetic rather than environmental variables (Anderson *et al.,* 2018). Furthermore, by comparing population performance in conditions representative of their native habitats, common garden studies facilitate the examination of local adaptation, aiding in the identification of adaptive traits, and elucidating the mechanisms of natural selection (Lee-Yaw *et al.,* 2020). Furthermore, by testing hypotheses on how gene-environment interactions shape phenotypic variation, common garden experiments can illuminate the processes underlying evolutionary change (Benestan *et al.,* 2016).

Despite their utility, common garden experiments have limitations that should be considered. Maron *et al.* (2018) noted that one disadvantage of common garden studies is that they may not fully account for the range of environmental factors that naturally occur across populations. This can result in biased estimates of trait heritability and genetic differentiation. Furthermore, since individuals are typically raised in a single, standardised environment that may not accurately reflect the diversity of environmental conditions found in nature, common garden experiments may overlook the importance of genotype-environment interactions in determining trait expression (Franks and Hoffmann, 2016). Additionally, common garden studies require significant effort and resources, including large sample sizes, rigorous experimental design, and ongoing monitoring to obtain accurate results (Hadfield *et al.,* 2017). Finally, because common garden studies frequently focus on desirable traits in controlled environments rather than in the context of genuine ecological interactions, their capacity to address questions about the ecological relevance of trait variation may be limited (Johnson and Stinchcombe, 2017). Despite these drawbacks, common garden experiments remain a valuable method to understand the genetic basis of phenotypic variation and the processes that drive evolutionary change in wild populations.

### 2.7.3 Cross environmental correlation

Cross-environmental correlation (CEC) is a statistical approach used to assess the consistency of phenotypic traits across different environments (Jones *et al.,* 2020). By analysing the correlation between trait values obtained in various environmental settings, researchers can understand how individuals or populations respond to environmental variation (Van Doorslaer *et al.,* 2020). In CEC, phenotypic traits are measured in multiple environments, and then the correlation coefficient between these traits across different conditions is calculated (Gienapp *et al.,* 2013). A high positive correlation indicates low phenotypic plasticity, suggesting that individuals maintain consistent expression of traits in all environments (Van Doorslaer *et al.,* 2020). In contrast, a low or negative correlation denotes considerable phenotypic plasticity, indicating that trait expression varies between environments (Sgrò *et al.,* 2016).

Researchers use CEC to study the genetic and environmental factors that underlie phenotypic plasticity and variation (Rellstab *et al.,* 2015). By measuring the degree of correlation between traits in different environments, they can determine the extent to which genetic or environmental factors influence trait expression (Gienapp *et al.,* 2013). This information helps to forecast how organisms will respond to future environmental changes and to understand how they adapt to changing environmental conditions (Rellstab *et al.,* 2015). The cross-environmental correlation can be represented in a scatter plot as shown in Figure 2.3. The X- and Y-axes are used to plot the trait values in each environment, and the best fit line illustrates the relationship between the two sets of values. The higher the correlation between the environments, the closer the points are to the line of best fit.

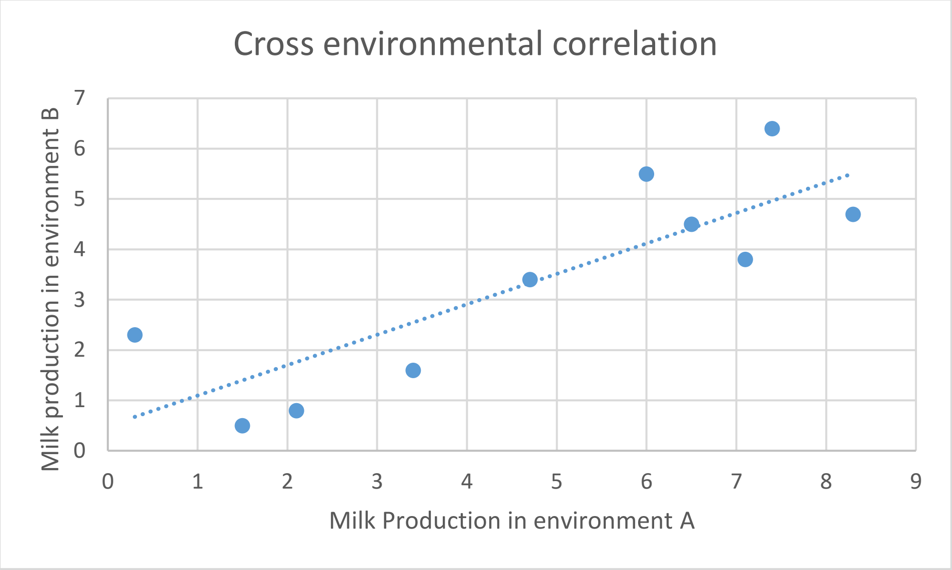

**Figure 2.3** cross environmental correlation scatter plot

The cross environmental correlation can also be represented mathematically as follows.

rxy = rAB – rA (1-rB)

Where:

- rxy is the correlation between environments A and B
- rAB is the correlation of trait X between environments A and B
- rA is the correlation of trait X within environment A
- rB is the correlation of trait X within environment B.

#### 2.7.3.1 Pros and Cons of Cross-environmental correlation

Cross-environmental correlation (CEC) provides a useful framework for understanding the consistency of trait expression across different environments, which can aid in predicting trait performance in novel or changing conditions (Marshall and Santiago, 2020). By assessing the degree of correlation between trait values recorded in various contexts, CEC enables researchers to evaluate the degree to which genetic factors influence trait expression across environmental gradients (Gienapp *et al.,* 2017). This technique is particularly helpful in breeding efforts aimed at generating cultivars or breeds with broad environmental adaptability because it offers insight into the genetic basis of genotype-by-environment interactions (Pfennig *et al.,* 2016). Furthermore, CEC facilitates the identification of genomic regions that are sensitive to environmental changes, which makes it possible to develop molecular markers for genomic prediction and marker-assisted selection (Zhang *et al.,* 2018). Furthermore, by identifying genotypes or populations with high adaptation potential in a variety of environments, CEC can guide conservation efforts by helping to prioritise conservation measures in the face of environmental change (Gienapp and Brommer, 2014).).

However, estimations of genetic correlations may be skewed because environmental factors that are not quantified or considered in the study may affect CEC (Santure *et al.,* 2018). Furthermore, because CEC assumes a linear relationship between trait values obtained in various contexts, it may not capture nonlinear or threshold-based responses to environmental gradients (Gienapp *et al.,* 2020). A common limitation of CEC studies is the availability of data from various environments, which can restrict the scope of analysis and generalisability of findings (Leimu *et al.,* 2016). Furthermore, interpreting CEC results can be challenging, as genetic correlations can vary depending on specific environmental factors or experimental setups used (Brommer *et al.,* 2018). Aside from these drawbacks, cross-environmental correlation remains a valuable method for investigating the connections between genotype and environment and expanding our knowledge of the ecological and evolutionary processes that influence trait variation in a variety of settings.

### 2.7.4 Heritability estimates

Heritability estimates quantify the proportion of observed variance in a trait or attribute within a population that can be attributed to genetic influences. This statistical metric expresses the extent to which genetic variation accounts for individual differences in a given attribute within a specific population (Khrystoforova *et al.,* 2021). According to Bloom *et al.* (2019), heritability estimates offer significant insight into the degree to which genetic factors within a population can account for phenotypic variance. Understanding the genetic basis of traits and their potential for phenotypic plasticity is heavily based on these estimates (Zeng *et al.,* 2020). By estimating the percentage of phenotypic variance attributable to genetic differences between individuals, heritability estimates provide a measure of the genetic contribution to trait expression (Bloom *et al.,* 2019). Phenotypic plasticity refers to the ability of individuals to develop distinct phenotypes in response to environmental stimuli (Schlichting and Wund, 2014). By comparing trait variation across different environments, heritability estimates can be used to evaluate the genetic basis of phenotypic plasticity (West-Eberhard, 2003). Limited phenotypic plasticity is suggested by high heritability estimates across environments, indicating strong genetic control over trait expression (Zhang *et al.,* 2021).

In contrast, low heritability estimates across habitats imply that environmental factors account for most of the variation in traits, demonstrating considerable phenotypic plasticity (Schlichting and Wund, 2014). These results emphasise how both genetic and environmental variables shape phenotypic variation and plasticity (West-Eberhard, 2003). To better understand phenotypic plasticity, heritability estimates offer a quantitative assessment of the relative contributions of genes and the environment to trait expression (Bloom *et al.,* 2019). Heritability estimates can also be represented by a bar chart, as shown in Figure 2.4 below. Each environment is represented by two bars by which the first bar represents the average trait of interest (e.g., the average milk production for each environment) in that environment, and the second bar represents heritability estimates in that environment. Linear models are commonly used for heritability estimates.

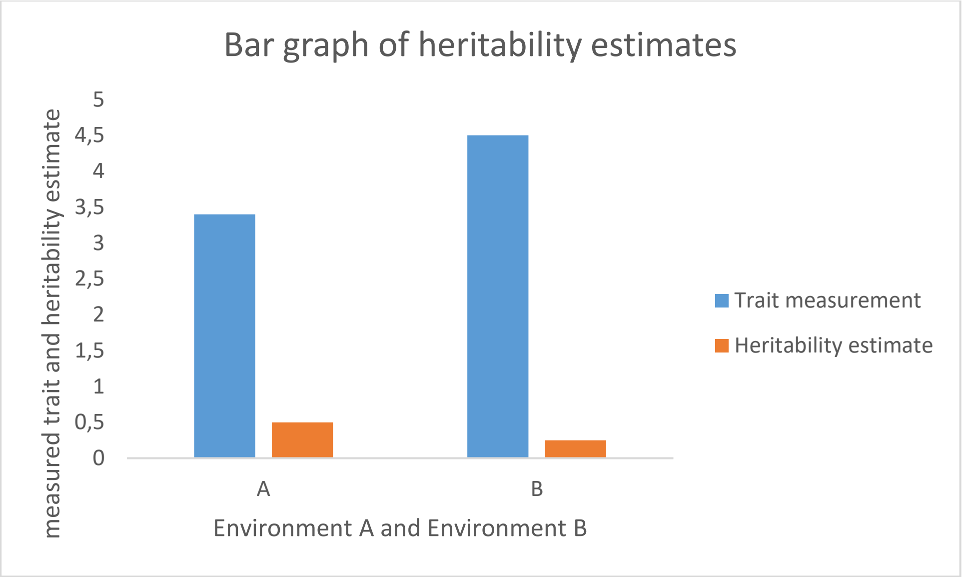

**Figure 2.4** Bar graph of heritability estimates

### 2.7.4.1 Pros and Cons of Heritability estimates

Heritability estimation is a valuable tool for determining the proportion of phenotypic variance attributable to genetic causes. This information can be used to understand the genetic basis of trait expression in different environmental contexts (Houle, 2016). By partitioning phenotypic variance into genetic and environmental components, heritability estimates allow researchers to evaluate the extent to which phenotypic plasticity is genetically controlled (Falconer and Mackay, 2018). This approach is particularly helpful in evolutionary biology and breeding programs because it facilitates the identification of genetic variants associated with adaptive phenotypic responses to changing environmental conditions (Bérénos *et al.,* 2014). Furthermore, heritability estimates can inform management plans and conservation efforts by providing predictions about how populations can evolve in response to environmental change (Kruuk *et al.,* 2018). Furthermore, heritability estimates offer a quantitative basis to understand the genetic architecture of complex traits and the potential for selection to influence phenotypic variation (Barton and Keightley, 2016).

Although useful, evaluating heritability as a measure of phenotypic plasticity has drawbacks that should be considered. Heritability estimates can be biased in terms of genetic variance due to environmental factors that are not sufficiently controlled or evaluated in the study (Kruuk *et al.,* 2017). Moreover, the generalisability of heritability estimates across different environments may be limited by their dependence on the specific environmental conditions in which they are measured (Stinchcombe and Kirkpatrick, 2012). Furthermore, heritability estimates offer a static measure of genetic influences that might not adequately capture the complexity of genotype-by-environment interactions, as they do not reflect dynamic responses to changing environmental conditions (Hoffmann and Merilä, 2017).). Finally, nonadditive genetic effects and gene-environment interactions can confound heritability estimates, making it more challenging to interpret data and identify the underlying genetic pathways (Zhou and Stephens, 2018). Despite these limitations, heritability estimation remains a valuable method for investigating phenotypic plasticity and expanding our knowledge of the genetics underlying trait variation.

### 2.7.5 Manipulative experiments

Controlled experiments, also known as intervention studies or manipulative experiments, represent a class of scientific investigations in which researchers purposely alter one or more variables to observe the effects on other variables (Aggarwal and Ranganathan, 2019). These experiments involve applying controlled environmental alterations to organisms to track their phenotypic responses (Huang *et al.,* 2021). By manipulating environmental parameters such as temperature, light or nutrient availability, researchers can assess the extent and magnitude of phenotypic diversity within a population (Aubin-Horth and Renn, 2009). Manipulative studies frequently use growth chambers and other controlled environments (Matesanz *et al.,* 2020). These sets of conditions allow researchers to isolate the impact of specific factors on phenotypic expression because environmental variables are precisely controllable (Whitney *et al.,* 2019).

Transplant experiments offer a second strategy in which individuals are transferred from one population or environment to a different, unfamiliar setting (Davies *et al.,* 2020). Using this technique, scientists can evaluate the degree of phenotypic variability between populations or genotypes (Richter-Boix *et al.,* 2021). Adaptive responses to changing environments have been studied in a variety of taxa, including microorganisms, plants, and animals, using transplant experiments (Huynh *et al.,* 2019).

In addition, reciprocal transplant trials involve individuals being transferred back and forth between dissimilar habitats (Donihue and Lambert, 2015). According to Räsänen and Kruuk (2007), these reciprocal transfers shed light on the genetic basis of phenotypic plasticity and local adaptation. By comparing an individual's performance in its native and foreign environments, researchers can determine the relative contributions of genetic and environmental factors to phenotypic variance (Burgarella *et al.,* 2021). Manipulative experiments are also presented by a bar graph as shown in Figure 2.5 below. This represents how the measured trait of interest changes in response to a changing environment (represented by the third bar under negative side), which shows the drop in the measured trait. The first and second bars represent two different environments where a trait was measured.

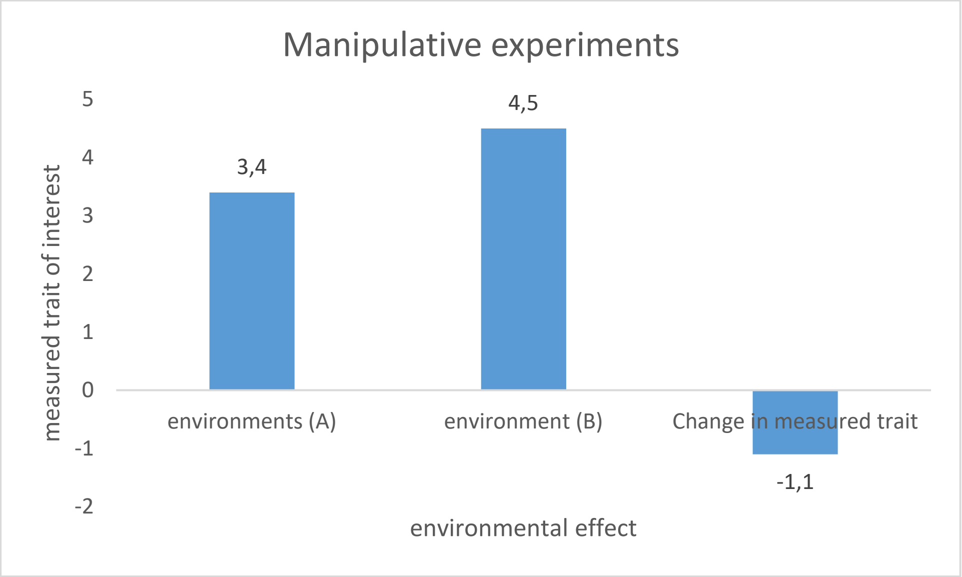

**Figure 2.5** Manipulative experiments bar graph

### 2.7.5.1 Pros and Cons of Manipulative Experiments

By actively altering environmental factors and tracking the resulting phenotypic changes, manipulative experiments offer a powerful method to investigate phenotypic plasticity. Researchers can determine the causal mechanisms underlying phenotypic responses by isolating the impact of specific factors on trait expression through environmental control (Calsbeek and Cox, 2010). This approach allows quantification of the direction and magnitude of phenotypic plasticity, which sheds light on the adaptive importance of plastic responses to environmental change (Whitman and Agrawal, 2018). Furthermore, by examining how different genotypes respond to the same environmental cues, manipulation studies allow researchers to investigate genotype-by-environment interactions (Donohue *et al.,* 2014). Manipulative experiments offer the flexibility to test hypotheses at various temporal and spatial scales, ranging from lab-based assays to field studies conducted in natural environments (Valladares *et al.,* 2014). Ultimately, manipulative experiments help advance our understanding of the ecological and evolutionary dynamics of natural populations by generating predictive models of phenotypic responses to future environmental change (Reed *et al.,* 2016).

However, factors outside of the researchers' control, including genetic variations between individuals or uncontrollable environmental conditions, may influence the outcomes of experiments (Ghalambor *et al.,* 2015). Because manipulation experiments often focus on isolating the impacts of single components, they may not capture the cumulative effects of multiple environmental factors that act together (Scheiner, 2016). Logistical difficulties and practical constraints may limit manipulative studies, especially when field testing is performed in complex natural settings (Williams *et al.,* 2018). Finally, phenotypic responses to environmental modification may differ based on the specific traits and species studied, meaning that the interpretation of experimental results may depend on the context (Ghalambor *et al.,* 2015).

### 2.7.8 Other methods of calculating phenotypic plasticity index (PPI)

#### 2.7.8.1 Variance-based method

Variance-based methods assess phenotypic plasticity by partitioning phenotypic variation using analysis of variance (ANOVA) (dos Santos *et al.,* 2023). This approach quantifies the phenotypic variation of a trait in a variety of environments, statistically separating the variation attributable to genetic factors, environmental factors, and genotype-by-environment interaction (dos Santos *et al.,* 2023).

**Procedure**: This method involves cultivating multiple individuals with diverse genotypes in a spectrum of environments. The phenotype of interest is measured for each individual in each environment, generating a data set comprising phenotypic values, genotypes, and environmental conditions (Grenier *et al.,* 2016). ANOVA is then employed to partition the total phenotypic variance into its components: genetic variance (VG), environmental variance (VE), and genotype-by-environment interaction variance (VGxE). The VGxE component is of particular importance, as it reveals the degree to which genotypes exhibit differential plastic responses to environmental variation (dos Santos *et al.,* 2023).

**Advantages and Disadvantages of the Variance-Based Method:** This method offers a statistically rigorous means to quantify and compare the plasticity of the phenotype between different traits and populations. By partitioning variance, it provides valuable information on the relative contributions of genetic and environmental factors to phenotypic variation (Grenier *et al.,* 2016). Variance-based methods require large sample sizes and meticulously controlled experimental designs to accurately estimate variance components. They are also susceptible to environmental heterogeneity and nonlinear genotype-by-environment interactions, which can confound the interpretation of results (Grenier *et al.,* 2016).

#### 2.7.8.2 Coefficient of variation method

The coefficient of variation (CV) method quantifies phenotypic plasticity by measuring the relative phenotypic variation across different environments (Matesanz *et al.,* 2021). This approach uses the coefficient of variation to describe the degree to which a phenotype changes in response to varying environmental conditions (Pélabon *et al.,* 2020).

**Procedure**: This method involves measuring a specific phenotypic trait for a group of individuals (typically of the same genotype or from a population) across a range of environments. For each environment, the mean phenotypic value is calculated. The coefficient of variation is then calculated as the ratio of the standard deviation of the phenotypic values to the mean phenotypic value in all environments tested (Oliver, 2024).

**Advantages and disadvantages of the coefficient-of-variation method:** CV is a dimensionless ratio that, when traits are assessed on the same scale, allows direct comparisons of plasticity across various features and species (Insee, 2016). It is particularly useful in studies where environmental conditions are well defined and controlled (Insee, 2016). The CV method is sensitive to scale effects, especially when comparing traits with different units of measurement (Pélabon *et al.,* 2020). It also assumes a linear relationship between the phenotype and the environment, which may not always hold (Oliver, 2024). Additionally, the CV provides no information about the direction or shape of the plastic response, only its magnitude (Insee, 2016).

### 2.7.8.3 Regression-based method

The regression-based method for calculating the phenotypic plasticity index involves analysing the relationship between phenotypic traits and environmental conditions through statistical regression techniques (Huang *et al.,* 2023).

**Procedure: The procedure typically starts with collecting phenotypic data from individuals in multiple environments.** For each individual, the trait of interest is measured, and these measurements are then subjected to regression analysis. A common approach is to use linear regression, where the dependent variable is the phenotypic trait and the independent variable is the environmental condition. The slope of the regression line represents the degree of plasticity; a steeper slope indicates a greater responsiveness of the phenotype to environmental changes, while a flatter slope suggests a lower plasticity (Liu *et al.,* 2021).

**Advantages and disadvantages of the regression-based method:** The regression-based method provides a clear quantitative measure of plasticity that can be compared between different genotypes and environments (Oliveira *et al.,* 2019). Allows the identification of specific relationships between traits and environmental factors, facilitating a deeper understanding of how organisms adapt to varying conditions (Huang *et al.,* 2023). One limitation is that this method assumes a linear relationship between the phenotype and the environment, which may not capture more complex interactions. Additionally, it can be sensitive to outliers or nonnormal distributions in the data, potentially skewing results (Liu *et al.,* 2021). The accuracy of this approach also depends on having sufficient data points across various environments to ensure robust regression estimates (Huang *et al.,* 2023).

### 2.8 Conclusion

This chapter has thoroughly examined the presence of Toggenburg dairy goats in South Africa, with a focus on milk production characteristics across various agro-ecological zones. An extensive review of the South African goat milk production sector has revealed the significance, challenges, trends, and potential for growth of the industry. Analysing the genetic makeup and behavioural traits of Toggenburg goats has provided valuable insights into their adaptability to diverse environmental settings, which is crucial to understanding the capacity of goats for milk production.

Furthermore, the chapter has examined the productive traits of Toggenburg goats, such as growth rates and reproductive success, providing information on the factors that directly influence milk production. In addition, it has explored the various environmental, genetic, animal-related and husbandry factors that affect goat milk production in South Africa. Phenotypic plasticity was defined along with the interplay between adaptive and non-adaptive plasticity.

A deeper understanding of the topic has emerged from the discussion of several approaches to evaluating phenotypic plasticity, including reaction norms, common garden experiments, cross-environmental correlation, heritability estimates, manipulative experiments, and methods to calculate the phenotypic plasticity index (PPI).). By establishing a foundation for future research, it is prudent to assess the animal and environmental factors responsible for milk production performance across the agro-ecological zones and genotypes of Toggenburg goats in South Africa.

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# CHAPTER 3

# ENVIRONMENTAL AND ANIMAL FACTORS AFFECTING MILK PRODUCTION OF TOGGENBURG GOAT IN SOUTH AFRICA.

## Abstract

Toggenburg dairy goats are important to the South African dairy sector due to their adaptability and milk yield. These traits are influenced by environmental and animal-related factors. This study aimed to evaluate the effects of these factors on the reproductive performance, milk production, and dairy value traits of Toggenburg goats in South Africa. Performance records (N=2417) were collected from a purposive sample of does in five agro-ecological zones: arid, semi-arid, sub-humid, humid, and temperate. Generalised linear models were used to estimate least squares means and analysis of variance was performed to partition variation using Minitab 18.1 software. Mean separation was carried out using Fisher's least significant difference (LSD) method at a level of significance of 5%. Pearson's correlation coefficients were calculated for significant random factors and milk variables. The results showed that the winter kidding season showed high kid status (0.6269±0.0820 healthy) *($p<0.05$),* while spring showed the highest somatic cell count (SCC) (302±103 cells/ml). AEZs significantly *($p<0.05$)* influenced the arid zone to produce the largest litter size (2.069±0.113 kids) and the temperate zone produced the highest lactation milk yield (647.32±5.59 kg). Blood breed purity levels showed a significant effect ($p<0.05$), with a high lactation milk yield in Founders (675.1±17.9 kg). Litter size was affected by dam parity *($p<0.05$),* with greater number of kids at parities 2 (1.9464±0.0984 %), 3 (1.947±0.100 %), 4 (2.052±0.108 %), 5 (1.958±0.115 %), and 7 (2.183±0.164 %). At advanced parities like 7 (38.19±4.49 %), 8 (28.77±4.82 %), 9 (38.06±6.62 %), and 10 (35.48±6.37 %), older dams had lower protein productions, but at parity 10, they had better milk persistency (81.54±8.18 %). In conclusion, kidding season, agro-ecological zones, genotype, dam parity, dam parity-by-kid sex, and kid sex-by-animal birth status significantly affect reproductive performance, milk production, and dairy value traits of Toggenburg goats.

**Keywords**: Agro-ecological zone, Persistency, breed purity levels, lactation milk yield, Temperate

## 3.1 Introduction

The Toggenburg goats, originally bred in Switzerland, play a crucial role in South Africa's livestock sector due to their resilience, high milk production, and adaptability (Sanon *et al.,* 2021; Mapiye *et al.,* 2023). Their milk is particularly valued in the dairy industry for its high butterfat and protein content (DALRRD, 2020). However, optimising the milk production of Toggenburg goats requires an advanced understanding of the complex interactions between environmental and animal factors (Dzama *et al.,* 2023). The potential for high milk production in these goats is influenced by various environmental and animal conditions, necessitating further research to enhance productivity in the South African context (Hlatini *et al.,* 2022).

As the importance of Toggenburg goats grows, the South African dairy industry faces challenges to maximise milk production due to a lack of comprehensive knowledge on the environmental and animal factors affecting production (Mlambo *et al.,* 2023; Banga *et al.,* 2022; Sebola *et al.,* 2021). There exists a knowledge gap regarding the specific opportunities and challenges faced by Toggenburg goat producers in South Africa, largely because previous research has focused on general aspects of goat husbandry and has been carried out in different geographical regions (Ndlovu *et al.,* 2022). This gap complicates efforts to optimise both milk yield and quality, particularly across South Africa's diverse agro-ecological zones, where varying climate and vegetation patterns demand specialised management strategies (Muchenje *et al.,* 2022).

To enhance the productivity of Toggenburg goat milk and ensure the sustainability of South Africa's dairy industry, it is essential to understand the intricate interactions between environmental and animal factors (Mapiye *et al.,* 2021; Ngongoni *et al.,* 2021; Sithole *et al.,* 2023). By examining the interactions between animal factors such as genotype, dam parity, litter size, and kid sex and environmental variables such as lactation duration, agro-ecological zone, and kidding season, this study seeks to close the current research gap on the effects of these variables on milk yield and quality across different agro-ecological zones in South Africa. Key milk quality traits are impacted by a wide range of environmental and animal factors that are intricately linked to the milk production of Toggenburg goats in South Africa. Factors such as agro-ecological zone, kidding season, and lactation length significantly impact milk urea nitrogen, somatic cell count, lactation milk yield, milk protein content, lactose concentration, and production persistency (Scano and Caboni, 2022). To optimise milk production while ensuring the health and welfare of Toggenburg goats in various environmental conditions throughout South Africa, management strategies must consider the dynamic relationships between these parameters and milk quality attributes. Therefore, the aim of the study was to assess key environmental and animal factors that affect reproductive performance, milk production traits, and dairy value traits of South African Toggenburg dairy goats.

## 3.2 Methodology and Analytical Procedures

### 3.2.1 Study site

The study was carried out in collaboration with the South African Toggenburg Breeders Association. South Africa, the southernmost nation on the African continent, shares borders with Namibia, Botswana, Zimbabwe, Lesotho and Eswatini. The country covers an area of approximately 1,221,040 square kilometres, located around 30.5595 ° S latitude and 22.9375 ° E longitude (Mdepha, 2022; Etaware, 2023). South Africa is characterised by diverse natural landscapes, including mountains, national parks, attractive beaches, savannahs, grasslands, and forests. The study sites consisted of farms located in different agro-ecological zones in Limpopo, Gauteng, Eastern Cape, Free State, Northwest, Mpumalanga, Western Cape, Northern Cape, and KwaZulu-Natal provinces. Table 3.1 presents the characteristics of these agro-ecological zones in South Africa.

Table 3. 1 The different agro-ecological zones in South Africa and their characteristics (Source: FAO, 2003).

| **Agro-ecological Zone** | **Predominant Province** | **Agro-ecological zones characteristics** | | |
|---|---|---|---|---|
| | | **Climate** | **Vegetation cover/ Biomes** | **Landforms and soils** |
| Arid | Northern Cape, parts of Limpopo, Northwest | Very low rainfall (<200 mm), High Temperatures (20-30°C) | Desert, Shrub land, Succulent Steppe | Sandy, low fertility (deserts, dunes) |
| Semi-arid | Northern Cape, Free State, Northwest, | Low rainfall (200-400 mm), Moderate Temperatures (15-25°C) | Grassland with scattered savanna trees, Thorn veld. | Sandy loam, moderate fertility (plains, plateaus) |

|  |  |  |  |  |
|---|---|---|---|---|
|  | Eastern Cape (parts) |  |  |  |
| Sub-humid | Limpopo (parts), Mpumalanga (parts), KwaZulu-Natal (parts), Eastern Cape (parts) | Moderate rainfall (400-600 mm), Moderate Temperatures (10-20°C) | Savanna with woodland patches, Thicket, Grassland in valleys | Clay loam, moderate fertility (rolling hills, mountains) |
| Humid | KwaZulu-Natal, Limpopo (parts), Mpumalanga (parts) | High rainfall (800-1200), Moderate Temperature (18-25°C) | Shrubs, ferns, flowering plants | Clay loam, moderate fertility (low laying coastal plains and rolling hills) |
| Temperate | Western Cape (southwest), Eastern Cape (south) | Moderate rainfall (500-800 mm) with cool, wet winters mild temperatures (8-12°C) and warm, dry summers warm temperatures (18-22°C) | Fynbos with renoster veld patches, temperate forests | Sandy loam, moderate fertility (mountains, coastal slopes) |

### 3.2.2 Study animals, sampling, and management

3.2.2.1 Study animals

The study used data from Toggenburg dairy goats, focusing exclusively on does with dam parity ranging from 1 to 10. All animals were officially registered and participated in the Milk Recording and Performance Testing Scheme conducted by the Animal Improvement Institute of the Agricultural Research Council of South Africa. The animal records analysed spanned from 1955 to 2018, providing a comprehensive dataset to evaluate various performance traits.

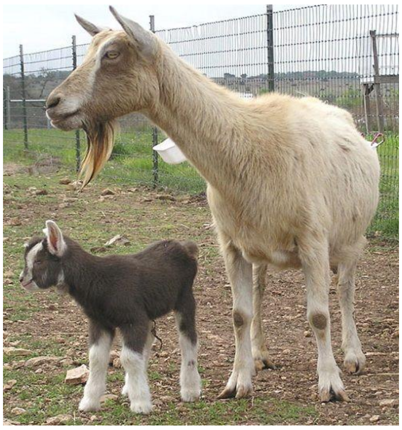


Figure 3. 1 Toggenburg goat dam with its kid (Aardvark, 2017).

### 3.2.2.2 Animal sampling

The study utilized a sample size of 2 417 Toggenburg dairy goats, determined based on the availability of performance records from farmers registered with the South African Studbook. A multistage sampling procedure was employed, which incorporates both purposive and convenience sampling techniques.

Sampling Stages:

1. First stage - Purposive Sampling: Five predominant agro-ecological zones were identified for their significant populations of Toggenburg goats: arid, semi-arid, sub-humid, humid, and temperate. These zones were selected based on their relevance to the study objectives.
2. Second Stage - Convenience Sampling: The farms and Toggenburg does with the required milk performance data were conveniently sampled from the identified agro-ecological zones. This approach allowed for efficient collection of relevant data from farms actively involved in Toggenburg goat production.

The sample size (n) was determined using Slovin's formula (Ryan, 2013), as it states clearly that it is suitable for determining sample size for large population sizes. The formula is represented in Figure 3.2, which illustrates how the sample size was derived based on the total population and the desired level of precision. This gave 2 417 does.

$$n = \frac{N}{1 + Ne^2}$$

where $n$ = sample size
$N$ = population size
$e$ = margin of error

Figure 3. 2 The Slovins' Formula of sample size (Ryan, 2013).

Arid zone: 343 x 15% = 363, Semi-arid: 343 x 3% = 242, Sub-humid: 343 x 3% = 242, Temperate: 343 x 74% = 1789.

In the arid agro-ecological zone, a sample size of three hundred and sixty-three (n = 363) goats with complete animal records was used. Both the semi-arid and sub-humid zones had a smaller sample size of two hundred and forty-two (n=242) goats each.

The temperate zone provided the largest number of records, with a sample size of one thousand seven hundred and eighty-nine (n=1789) goats. Within each agro-ecological zone, convenience sampling was used to select records that were readily available and accessible. This approach focused on goats with complete performance records that span from birth to the end of their reproductive period. The aim was to meet the overall sample size (n=2417) of farms representing the diverse agro-ecological zones.

#### 3.2.2.3 Animal Management

The animals were managed following conventional husbandry breed standards for feeding, vaccination, healthcare, and breeding. Rearing practices adhered to a semi-intensive production system, where the flock foraged in the veld during the day and returned to the pens at night. Does in their final month of pregnancy received a modified feeding schedule supplemented with a concentrate mix to meet the nutritional needs of the developing foetus and prevent pregnancy toxemia. Water was provided ad libitum throughout the lifetime of the goats. A mating ratio of 1:20 was used. The young bucks were removed from the flock before reaching reproductive maturity, according to the breeding association regulations. To prevent abortion, chlamydia was treated prior to the breeding season, along with internal parasites, nasal worms, and other common conditions. Annual vaccinations against bluetongue and pulpy kidney were administered.

### 3.2.3 Study design, data collection, and editing.

#### 3.2.3.1 Study design

This study used a longitudinal observational design that incorporates complex statistical models with fixed and random factors. Secondary data on reproductive and milk production traits of registered Toggenburg goats were collected. This dataset also included information on environmental and animal factors, as highlighted in table 3.2.

Table 3. 2: An illustration of the factors and factor levels that were used in the study.

| **Factor** | **Factor level** |
|---|---|
| Breed | Toggenburg |
| Agro-ecological zones | Arid, semi-arid, sub-humid, and temperate. |

| | |
|---|---|
| Sample size | 2 417 does |
| Experimental units | Goats (does) |
| Factors evaluated | Fixed factors: Dam parity (1-10), dam kidding season (summer, autumn, winter, spring), blood breed purity levels (F0 - founders, CP - <75%, A – 87.5 – 93.75%, B – 75 – 87.87%, SP - >93.75%), and agro-ecological zones.<br>Random Factors**:** Dam age at kidding, animal birth year, and lactation length (1955 to 2018). |
| Variables gathered | Dam longevity, kidding ease (KE), prolificacy/litter size, kidding interval (KI), age at first kidding (AFK), kid status, animal birth status, lactation milk yield (LMY), lactation protein yield (LPY), lactation fat yield (LFY), somatic cell count (SCC), milk urea nitrogen (MUN), lactation indices and milk persistency (MP) |

Table 3. 3: Measured traits, descriptions, and standard method of measurement

| **Traits** | | **Description** |
|---|---|---|
| **Reproductive** | Kidding Ease | Refers to the practice of assisting goats in giving birth with a minimum of stress and interruption (Kentucky State University, 2024)<br>(Scale: 1 = no assistance, 2 = minor assistance, 3 = major assistance, 4 = caesarean section, 5 = veterinary assistance)<br>. |
| | Kid Status | Refers to the overall well-being and freedom from diseases of individual animal during birth (Constantin Cerbu *et al.,* 2023)<br>(Scale: 1 = healthy, 2 = sick, 3 = injured, 4 = disabled) |
| | Litter Size | The total number of kids a goat or doe has in one kidding (BiologyOnline, 2021).<br>(Method: Direct count) |
| | A_BSTAT | Refers to the difficulty of animal at birth (Allen, 2018).<br>(Scale: 1 = no difficulty, 2 = slightly, 3 = moderate, 4 = severe, 5 = extreme) |
| **Milk production** | LMY | The quantity of milk a goat produces while lactating (Moran, 2015).<br>(Method: Calibrated scale) |
| | LPY | Amount of protein a goat makes in its milk while lactating (Roy, 2020).<br>(Method: Kjeldahl method) |
| | LFY | Amount of fat a goat makes in its milk while lactating (Daley *et al.,* 2022).<br>(Method: Infrared spectroscopy) |
| | SCC | A measure of number of somatic cells in a milk quality (Sun *et al.,* 2023). |

| | | |
|---|---|---|
| | | (Method: California Mastitis Test) |
| | MUN | An indicator of nitrogen efficiency, goat health, and environmental impact (Chrystal, 2024).<br>(Method: Infrared spectroscopy) |
| **Dairy value** | LI | A measure of a goat's milk production efficiency, calculated by combining various lactation traits (Da costa and Bluck, 2010).<br>(Method: LI = total lactation milk yield (kg)/lactation length (days)) |
| | LVI | A measure of a goat's lactation performance, considering both milk yield and persistency (Da costa and Bluck, 2010). |
| | MP | Refers to a goat's ability to maintain milk production throughout the lactation period (Moran, 2015).<br>(Method: MP = 100*(peak milk yield-post peak mil yield)/peak milk yield) |
| | DL | Refers to the length of time a dam remains productive and able to breed, produce kids and milk (Pellerin and Browning, 2012).<br>(Method: Death date-birth date) |

#### 3.2.3.2 Data collection and editing

The study used data from 2 417 registered goats, sourced from the LOGIX database of Toggenburg dairy goats stud in South Africa. The dataset comprised details such as animal ID, birth date, dam parity, farm, dam kidding dates, litter size, lactation length, and agro-ecological zones.

Using Microsoft Excel version 2020, animals with incomplete records were excluded to ensure data integrity. Additionally, records with missing or incorrect details regarding fixed factors and random factors, as well as duplicates, were removed to improve the precision of the analysis. The kidding season was determined on the date of the kidding. Lactation length was calculated by subtracting the date of kidding from the end of the lactation date. The date of birth was adjusted to derive both the season of birth and the birth year.

### 3.2.4 Data analysis

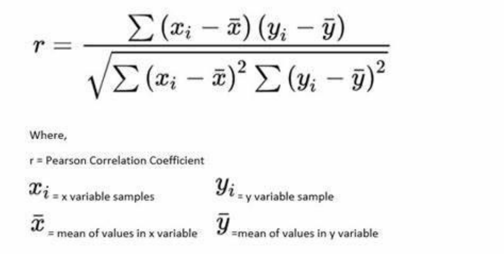
The significance of fixed and random was assessed using least-squares analysis of variance (ANOVA) through General Linear Model (GLM) function in Minitab 18.1 (2017) statistical software. Mean separations between groups were performed using Fisher's least significant difference (LSD) method, with a confidence level of 95%. The GLM, in matrix notation, is presented as:

Y = Xb + Zu + e

Whereby:

- Y= vector of observations (reproductive traits, milk production traits, and dairy value traits)
- b= vector of fixed effects (kidding season, birth year, agro-ecological zone, kid sex, dam parity, litter size)
- u= vector of random effects (dam age, lactation length)
- e= vector of random residual effects.
- X and Z are incidence matrices relating responses to the fixed and random effects, respectively.

To examine the relationship among random factors, milk production and component traits, Pearson's correlation coefficients were calculated using the formula below.



$$r = \frac{\sum (x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum (x_i - \bar{x})^2 \sum (y_i - \bar{y})^2}}$$

Where,

r = Pearson Correlation Coefficient

$x_i$ = x variable samples $y_i$ = y variable sample

$\bar{x}$ = mean of values in x variable $\bar{y}$ =mean of values in y variable

Where:
xi and yi are individual sample points.
$\bar{x}$ is the mean of x-values.
$\bar{y}$ is the mean of y-values

### 3.3 Results

#### 3.3.1 Effect of environmental factors on reproductive, milk production, and dairy vale traits of Toggenburg goats.

Kidding season had a significant effect ($p<0.05$) on kid status and somatic cell count as shown in Table 3.4. Agro-ecological zone had a significant effect ($p<0.05$) on kidding ease, kid status, litter size, lactation milk yield, lactation fat yield, somatic cell count, and milk urea nitrogen as represented in Table 3.5.

Table 3. 4: Effect of kidding season on reproductive, milk production, and dairy value traits of Toggenburg goats in South Africa.

| | Kidding seasons | | | |
|---|---|---|---|---|
| | Autumn | Spring | Summer | Winter |
| N | 6 | 701 | 160 | 790 |
| Traits | | | | |
| **Reproductive** | | | | |
| KE | 0.612±0.231$^{a}$ | 0.744±0.106$^{a}$ | 0.526±0.118$^{a}$ | 0.7009±0.0913$^{a}$ |
| KS | 0.708±0.207$^{ab}$ | 0.6240±0.0950$^{ab}$ | 0.363±0.106$^{b}$ | 0.6269±0.0820$^{a}$ |
| LS | 1.962±0.267$^{a}$ | 1.886±0.122$^{a}$ | 1.963±0.136$^{a}$ | 1.952±0.106$^{a}$ |
| A_BSTAT | 1.755±0.301$^{a}$ | 1.637±0.138$^{a}$ | 1.543±0.154$^{a}$ | 1.665±0.119$^{a}$ |
| AFK | * | 388.9±11.5$^{a}$ | 396.3±15.4$^{a}$ | 381.5±12.2$^{a}$ |
| **Milk production** | | | | |
| LMY | 632.1±67.5$^{a}$ | 624.7±47.6$^{a}$ | 646.8±49.2$^{a}$ | 618.9±47.6$^{a}$ |
| LPY | 32.88±5.60$^{a}$ | 38.93±3.95$^{a}$ | 39.76±4.08$^{a}$ | 38.25±3.95$^{a}$ |
| LFY | 48.19±5.58$^{a}$ | 41.88±3.94$^{a}$ | 41.84±4.07$^{a}$ | 42.67±3.94$^{a}$ |
| SCC | 164±146$^{ab}$ | 302±103$^{a}$ | 225±106$^{b}$ | 283±103$^{ab}$ |
| MUN | 22.76±4.52$^{a}$ | 19.76±3.19$^{a}$ | 20.87±3.30$^{a}$ | 19.84±3.19$^{a}$ |
| **Dairy value** | | | | |
| LI | 111.0±18.7$^{a}$ | 106.3±13.2$^{a}$ | 109.6±13.6$^{a}$ | 106.5±13.2$^{a}$ |
| LVI | 220.0±30.2$^{a}$ | 228.4±21.3$^{a}$ | 228.7±22.0$^{a}$ | 226.9±21.3$^{a}$ |
| MP | 68.15±7.18$^{a}$ | 70.53±5.07$^{a}$ | 69.87±5.24$^{a}$ | 70.57±5.07$^{a}$ |
| DL | 6.25±4.07$^{a}$ | 8.40±1.44$^{a}$ | 8.66±1.49$^{a}$ | 8.74±1.44$^{a}$ |

*N = Number of records, KE = kidding ease, KS = kid status, LS = litter size, AFK = age at first kidding, LMY = lactation milk yield, LPY = lactation protein yield, LFY = lactation fat yield, SCC = somatic cell count, MUN = milk urea nitrogen, LI = lactation index, LVI = lactation value index, MP = milk persistency, DL = dam longevity, * = values not computable. Means with different superscripts within a row are significantly different at P<0.05.*

Table 3. 5: Effect of agro-ecological zones on reproductive, milk production, and dairy value traits of Toggenburg goats in South Africa.

| | Agro-Ecological Zones (AEZ) | | | | |
|---|---|---|---|---|---|
| Traits | Arid | Semi-arid | Sub-humid | Humid | Temperate |
| N | 32 | 114 | 49 | 0 | 742 |
| Traits | | | | | |
| **Reproductive** | | | | | |
| KE | 0.5437±0.0935$^{ab}$ | 0.8526±0.0917$^{a}$ | 0.3025±0.0753$^{b}$ | * | 0.4113±0.0280$^{b}$ |
| KS | 0.9243±0.0996$^{a}$ | 0.5735±0.0978$^{b}$ | 0.5444±0.0803$^{b}$ | * | 0.6613±0.0299$^{b}$ |
| LS | 2.069±0.113$^{a}$ | 1.638±0.111$^{b}$ | 1.8266±0.0908$^{ab}$ | * | 1.7235±0.0338$^{b}$ |
| AFK | 377.9±14.4$^{a}$ | 405.2±15.5$^{a}$ | 389.6±14.6$^{a}$ | * | 382.8±11.2$^{a}$ |
| **Milk production** | | | | | |
| LMY | 656.1±18.6$^{ab}$ | 619.9±18.3$^{ab}$ | 616.5±15.0$^{b}$ | * | 647.32±5.59$^{a}$ |
| LPY | 37.54±1.56$^{a}$ | 34.42±1.53$^{a}$ | 36.90±1.25$^{a}$ | * | 34.606±0.467$^{a}$ |
| LFY | 37.30±1.55$^{b}$ | 42.06±1.52$^{a}$ | 36.89±1.25$^{b}$ | * | 39.218±0.464$^{ab}$ |
| SCC | 407.5±39.8$^{a}$ | 163.2±39.0$^{b}$ | 483.3±32.0$^{a}$ | * | 421.8±11.9$^{a}$ |
| MUN | 20.19±1.33$^{b}$ | 21.77±1.31$^{ab}$ | 25.79±1.07$^{a}$ | * | 21.306±0.400$^{b}$ |
| **Dairy value** | | | | | |
| LI | 90.85±5.16$^{a}$ | 96.42±5.07$^{a}$ | 86.60±4.16$^{a}$ | * | 89.81±1.55$^{a}$ |
| LVI | 229.68±8.38$^{a}$ | 231.67±8.22$^{a}$ | 226.33±6.75$^{a}$ | * | 227.69±2.51$^{a}$ |
| P | 75.50±1.98$^{a}$ | 74.93±1.94$^{a}$ | 74.67±1.59$^{a}$ | * | 73.639±0.593$^{a}$ |
| DL | 7.87±1.03$^{a}$ | 8.09±1.19$^{a}$ | 7.685±0.735$^{a}$ | * | 7.503±0.436$^{a}$ |

*N = Number of records, KE = kidding ease, KS = kid status, LS = litter size, AFK = age at first kidding, LMY = lactation milk yield, LPY = lactation protein yield, LFY = lactation fat yield, SCC = somatic cell count, MUN = milk urea nitrogen, LI = lactation index, LVI = lactation value index, MP = milk persistency, DL = dam longevity, * = data not available. Means with different superscripts within a row are significantly different at P<0.05.*

### 3.3.2 Effect of animal factors on reproductive, milk production, and dairy value traits.

Table 3.6 shows the effect of the blood purity levels of the breed, which was significant ($p<0.05$) on kidding ease, kid status, animal birth status, lactation milk yield, and milk urea nitrogen, suggesting that these traits are influenced by seasonal changes. Dam parity was only significant ($p<0.05$) on litter size, with parities 2, 3, 4, 5, and 7 producing a high number of kids. Additionally, lactation protein production was significantly influenced by parities 7, 8, 9, and 10, while milk persistency was notably affected only in parity 10 as shown in Table 3.7. Whereas kid sex, litter size, and animal birth status did not show a significant effect ($p>0.05$) with reference to the reproductive, milk production, and dairy value traits of Toggenburg goats, highlighting that these traits are not influenced by varying environmental climatic conditions.

Table 3. 6: Effect of genotype on reproductive, milk production, and dairy value traits of Toggenburg goats in South Africa.

| | **Breed purity levels (AS)** | | | | |
|---|---|---|---|---|---|
| | F0 Founders | CP Commercial purebred | Appendix A animals | Appendix B animals | Stud Book Proper animals |
| **N** | 82 | 0 | 175 | 207 | 473 |
| **Traits** | | | | | |
| **Reproductive** | | | | | |
| KE | 0.5347±0.0897$^{ab}$ | * | 0.6357±0.0486$^{a}$ | 0.5069±0.0487$^{b}$ | 0.4327±0.0376$^{b}$ |
| KS | 0.4818±0.0956$^{b}$ | * | 0.7847±0.0518$^{a}$ | 0.6977±0.0519$^{ab}$ | 0.7394±0.0401$^{a}$ |
| LS | 1.824±0.108$^{a}$ | * | 1.7917±0.0586$^{a}$ | 1.8152±0.0588$^{a}$ | 1.8262±0.0454$^{a}$ |
| A_BSTAT | 1.689±0.156$^{abc}$ | * | 1.461±0.132$^{c}$ | 1.660±0.131$^{b}$ | 1.790±0.129$^{a}$ |
| AFK | 388.5±19.0$^{a}$ | * | 389.2±12.5$^{a}$ | 383.3±12.2$^{a}$ | 394.5±11.2$^{a}$ |
| **Milk production** | | | | | |
| LMY | 675.1±17.9$^{a}$ | * | | | 616.50±7.50$^{b}$ |
| LPY | 36.21±1.49$^{a}$ | * | 626.15±9.69$^{ab}$ | 622.09±9.72$^{ab}$ | 35.685±0.626$^{a}$ |

|  |  |  |  |  |  |
|---|---|---|---|---|---|
| LFY | 38.75±1.49$^{a}$ | * | 35.006±0.809$^{a}$ | 36.563±0.811$^{a}$ | 38.979±0.623$^{a}$ |
| SCC | 402.9±38.1$^{a}$ | * | 38.931±0.804$^{a}$ | 38.808±0.807$^{a}$ | 356.9±16.0$^{a}$ |
| MUN | 25.76±1.28$^{a}$ | * | 364.0±20.7$^{a}$ | 351.9±20.7$^{a}$ | 22.841±0.536$^{b}$ |
| **Dairy value** |  |  |  |  |  |
| LI | 91.60±4.95$^{a}$ | * | 90.05±2.68$^{a}$ | 91.89±2.69$^{a}$ | 90.15±2.08$^{a}$ |
| LVI | 233.82±8.04$^{a}$ | * | 223.20±4.35$^{a}$ | 230.48±4.37$^{a}$ | 227.88±3.37$^{a}$ |
| MP | 71.56±1.90$^{a}$ | * | 74.53±1.03$^{a}$ | 74.47±1.03$^{a}$ | 75.188±0.795$^{a}$ |
| DL | 7.20±1.71$^{a}$ | * | 7.642±0.465$^{a}$ | 8.151±0.503$^{a}$ | 8.147±0.430$^{a}$ |

*N = Number of records, KE = kidding ease, KS = kid status, LS = litter size, AFK = age at first kidding, LMY = lactation milk yield, LPY = lactation protein yield, LFY = lactation fat yield, SCC = somatic cell count, MUN = milk urea nitrogen, LI = lactation index, LVI = lactation value index, MP = milk persistency, DL = dam longevity, * = data not available. Means with different superscripts within a row are significantly different at P<0.05.*

Table 3. 7: Effect of dam parity on reproductive, milk production, and dairy value traits of Toggenburg goats in South Africa

| | **Dam parity** | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| **N** | 268 | 201 | 168 | 128 | 86 | 45 | 21 | 14 | 3 | 3 |
| **Traits** | | | | | | | | | | |
| **Reproductive** | | | | | | | | | | |
| KE | 0.5747±0.0829$^{a}$ | 0.6248±0.0852$^{a}$ | 0.7022±0.0867$^{a}$ | 0.6739±0.0932$^{a}$ | 0.7174±0.0995$^{a}$ | 0.617±0.116$^{a}$ | 0.706±0.142$^{a}$ | 0.669±0.163$^{a}$ | 0.472±0.308$^{a}$ | 0.700±0.306$^{a}$ |
| KS | 0.6352±0.0744$^{a}$ | 0.6007±0.0764$^{a}$ | 0.6381±0.0778$^{a}$ | 0.6128±0.0836$^{a}$ | 0.5938±0.0893$^{a}$ | 0.519±0.104$^{a}$ | 0.595±0.127$^{a}$ | 0.623±0.146$^{a}$ | 0.403±0.276$^{a}$ | 0.584±0.275$^{a}$ |
| LS | 1.6950±0.0958$^{b}$ | 1.9464±0.0984$^{a}$ | 1.947±0.100$^{a}$ | 2.052±0.108$^{a}$ | 1.958±0.115$^{a}$ | 1.883±0.134$^{ab}$ | 2.183±0.164$^{a}$ | 1.750±0.189$^{ab}$ | 2.457±0.355$^{ab}$ | 1.539±0.354$^{ab}$ |
| A_BS TAT | 1.707±0.108$^{a}$ | 1.710±0.111$^{a}$ | 1.651±0.113$^{a}$ | 1.582±0.122$^{a}$ | 1.567±0.130$^{a}$ | 1.528±0.151$^{a}$ | 1.418±0.185$^{a}$ | 1.563±0.213$^{a}$ | 2.233±0.401$^{a}$ | 1.542±0.400$^{a}$ |
| **Milk production** | | | | | | | | | | |
| LMY | 624.3±47.5$^{a}$ | 650.0±48.3$^{a}$ | 652.0±46.7$^{a}$ | 655.4±48.3$^{a}$ | 663.4±49.1$^{a}$ | 664.2±50.8$^{a}$ | 627.6±54.2$^{a}$ | 581.8±58.1$^{a}$ | 661.3±79.8$^{a}$ | 526.1±76.8$^{a}$ |
| LPY | 38.78±3.94$^{a}$ | 40.54±4.00$^{a}$ | 38.42±3.88$^{a}$ | 38.16±4.01$^{a}$ | 38.74±4.08$^{a}$ | 39.42±4.21$^{a}$ | 38.19±4.49$^{ab}$ | 28.77±4.82$^{b}$ | 38.06±6.62$^{ab}$ | 35.48±6.37$^{ab}$ |
| LFY | 43.20±3.93$^{a}$ | 44.38±3.99$^{a}$ | 43.86±3.86$^{a}$ | 44.67±4.00$^{a}$ | 43.35±4.06$^{a}$ | 43.10±4.20$^{a}$ | 43.19±4.48$^{a}$ | 43.94±4.80$^{a}$ | 42.59±6.60$^{a}$ | 44.16±6.35$^{a}$ |
| SCC | 293±103$^{a}$ | 266±104$^{a}$ | 263±101$^{a}$ | 241±104$^{a}$ | 245±106$^{a}$ | 288±110$^{a}$ | 204±117$^{a}$ | 243±126$^{a}$ | 168±173$^{a}$ | 223±166$^{a}$ |
| MUN | 20.04±3.19$^{a}$ | 21.30±3.23$^{a}$ | 20.53±3.13$^{a}$ | 20.15±3.24$^{a}$ | 21.88±3.29$^{a}$ | 21.66±3.40$^{a}$ | 22.46±3.63$^{a}$ | 22.26±3.89$^{a}$ | 12.55±5.35$^{a}$ | 25.23±5.15$^{a}$ |
| **Dairy value** | | | | | | | | | | |
| LI | 109.8±13.2$^{a}$ | 118.0±13.4$^{a}$ | 112.0±12.9$^{a}$ | 113.4±13.4$^{a}$ | 112.3±13.6$^{a}$ | 112.7±14.0$^{a}$ | 106.7±15.0$^{a}$ | 88.8±16.1$^{a}$ | 110.3±22.1$^{a}$ | 99.9±21.3$^{a}$ |
| LVI | 231.6±21.3$^{a}$ | 237.6±21.6$^{a}$ | 233.5±20.9$^{a}$ | 230.2±21.6$^{a}$ | 235.5±22.0$^{a}$ | 225.0±22.7$^{a}$ | 218.4±24.2$^{a}$ | 197.9±26.0$^{a}$ | 210.3±35.7$^{a}$ | 240.0±34.4$^{a}$ |
| MP | 72.40±5.06$^{ab}$ | 71.47±5.14$^{ab}$ | 70.45±4.97$^{ab}$ | 72.36±5.14$^{ab}$ | 71.79±5.23$^{ab}$ | 68.36±5.40$^{ab}$ | 66.36±4.76$^{ab}$ | 70.21±6.18$^{ab}$ | 52.56±8.49$^{b}$ | 81.54±8.18$^{a}$ |
| DL | 7.98±1.67$^{a}$ | 8.63±1.68$^{a}$ | 8.64±1.69$^{a}$ | 9.17±1.73$^{a}$ | 8.48±1.79$^{a}$ | 7.72±1.84$^{a}$ | 7.95±1.94$^{a}$ | 7.04±2.15$^{a}$ | 7.31±2.82$^{a}$ | 7.23±2.81$^{a}$ |

*N = Number of records, KE = kidding ease, KS = kid status, LS = litter size LMY = lactation milk yield, LPY = lactation protein yield, LFY = lactation fat yield, SCC = somatic cell count, MUN = milk urea nitrogen, LI = lactation index, LVI = lactation value index, MP = milk persistency, DL = dam longevity. Means with different superscripts within a row are significantly different at $P<0.05$*

### 3.3.3 Effect of Genotype-by-environmental (GXE) interactions on reproductive, milk production, and dairy value traits.

The analysis did not reveal significant effects (*p*>0.05) for interactions between GenotypeXKid-sex, AEZXkid-sex, AEZXlitter-size, Kid-sexXLitter-size, Litter-sizeXAnimal-birth-status. However, dam parityXkid sex interactions significantly affected (*p*<0.05) lactation milk yield with parities 2, 3, and 5, producing more milk in only male kids, whereas parities 4 and 6 showed higher milk production in both sexes, as detailed in Table 3.9. Kid-sexXAnimal-birth-status also significantly affected (*p*<0.05) milk urea nitrogen with female kids experiencing severe birth difficulties resulting in high milk urea nitrogen levels, as highlighted in Table 3.10.

Table 3. 8: Effect of dam parityXkid sex on milk production and dairy value traits of Toggenburg goats in South Africa.

| **DP X KS** | **N** | **Traits** | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | **Milk production** | | | | | **Dairy value** | | |
| | | LMY | LPY | LFY | SCC | MUN | LI | LVI | MP |
| 1 Female | 187 | 633.8±50.5$^{ab}$ | 39.80±4.19$^{a}$ | 44.48±4.17$^{a}$ | 273±109$^{a}$ | 20.92±3.38$^{a}$ | 116.2±14.2$^{a}$ | 228.7±22.6$^{a}$ | 67.51±5.37$^{a}$ |
| 1 Male | 81 | 614.8±52.6$^{ab}$ | 37.76±4.36$^{a}$ | 41.93±4.35$^{a}$ | 313±114$^{a}$ | 19.15±3.53$^{a}$ | 103.4±14.6$^{a}$ | 234.6±23.5$^{a}$ | 77.30±5.60$^{a}$ |
| 2 Female | 151 | 649.4±50.9$^{ab}$ | 39.41±4.22$^{a}$ | 46.35±4.21a | 234±110$^{a}$ | 21.87±3.41$^{a}$ | 121.2±14.1$^{a}$ | 235.4±22.8$^{a}$ | 67.21±5.42$^{a}$ |
| 2 Male | 50 | 650.6±53.3$^{a}$ | 41.66±4.42$^{a}$ | 42.42±4.41$^{a}$ | 299±115$^{a}$ | 20.73±3.57$^{a}$ | 114.7±14.8$^{a}$ | 239.8±23.8$^{a}$ | 75.73±5.67$^{a}$ |
| 3 Female | 132 | 647.8±50.7$^{ab}$ | 38.24±4.20$^{a}$ | 46.51±4.19$^{a}$ | 243±110$^{a}$ | 21.03±3.29$^{a}$ | 118.4±14.0$^{a}$ | 234.0±22.7$^{a}$ | 67.89±5.39$^{a}$ |
| 3 Male | 36 | 656.3±51.0$^{a}$ | 38.61±4.23$^{a}$ | 41.21±4.22$^{a}$ | 283±110$^{a}$ | 20.04±3.42$^{a}$ | 105.7±14.1$^{a}$ | 233.0±22.8$^{a}$ | 73.02±5.43$^{a}$ |
| 4 Female | 103 | 661.6±51.4$^{a}$ | 39.81±4.26$^{a}$ | 44.40±4.25$^{a}$ | 227±111$^{a}$ | 21.82±3.44$^{a}$ | 117.5±14.2$^{a}$ | 228.1±23.0$^{a}$ | 68.33±5.47$^{a}$ |
| 4 Male | 25 | 649.1±55.0$^{a}$ | 36.51±4.56$^{a}$ | 44.94±4.55$^{a}$ | 255±119$^{a}$ | 18.48±3.68$^{a}$ | 109.3±15.2$^{a}$ | 232.2±24.6$^{a}$ | 76.39±5.85$^{a}$ |
| 5 Female | 65 | 658.4±52.2$^{ab}$ | 37.58±4.33$^{a}$ | 44.64±4.31$^{a}$ | 242±113$^{a}$ | 22.14±3.49$^{a}$ | 113.3±14.4$^{a}$ | 228.0±23.3$^{a}$ | 68.09±5.55$^{a}$ |
| 5 Male | 21 | 668.3±55.6$^{a}$ | 39.91±4.61$^{a}$ | 42.06±4.60$^{a}$ | 247±120$^{a}$ | 21.62±3.72$^{a}$ | 111.2±15.4$^{a}$ | 243.0±24.9$^{a}$ | 75.48±5.92$^{a}$ |
| 6 Female | 33 | 670.4±53.9$^{a}$ | 40.25±4.47$^{a}$ | 45.39±4.46$^{a}$ | 257±117$^{a}$ | 21.74±3.61$^{a}$ | 119.9±14.9$^{a}$ | 232.5±24.1$^{a}$ | 66.01±5.74$^{a}$ |
| 6 Male | 12 | 658.0±59.5$^{a}$ | 38.58±4.93$^{a}$ | 40.81±4.92$^{a}$ | 320±129$^{a}$ | 21.59±3.99$^{a}$ | 105.6±16.5$^{a}$ | 217.5±26.6$^{a}$ | 71.26±6.33$^{a}$ |
| 7 Female | 16 | 634.2±57.1$^{ab}$ | 36.78±4.73$^{a}$ | 44.27±4.72$^{a}$ | 235±123$^{a}$ | 23.69±3.82$^{a}$ | 108.7±15.8$^{a}$ | 214.7±25.5$^{a}$ | 62.30±6.07$^{a}$ |
| 7 Male | 5 | 621.1±67.9$^{ab}$ | 39.60±5.63$^{a}$ | 42.12±5.61$^{a}$ | 173±147$^{a}$ | 21.24±4.55$^{a}$ | 104.6±18.8$^{a}$ | 222.2±30.4$^{a}$ | 70.41±7.22$^{a}$ |
| 8 Female | 11 | 627.6±59.3$^{ab}$ | 32.69±4.92$^{a}$ | 45.42±4.90$^{a}$ | 249±128$^{a}$ | 25.27±3.97$^{a}$ | 105.7±16.4$^{a}$ | 217.2±26.5$^{a}$ | 65.25±6.32$^{a}$ |
| 8 Male | 3 | 536.0±77.8$^{ab}$ | 24.84±6.45$^{a}$ | 42.46±6.43$^{a}$ | 237±168$^{a}$ | 19.25±5.21$^{a}$ | 71.9±21.5$^{a}$ | 178.7±34.8$^{a}$ | 75.18±8.28$^{a}$ |
| 9 Female | 2 | 682.5±86.5$^{ab}$ | 41.13±7.18$^{a}$ | 41.38±7.15$^{a}$ | -40±187$^{a}$ | 19.58±5.80$^{a}$ | 114.1±23.9$^{a}$ | 191.4±37.8$^{a}$ | 57.91±9.21$^{a}$ |
| 9 Male | 1 | 640±116$^{ab}$ | 34.99±9.59$^{a}$ | 43.80±9.57$^{a}$ | 375±250$^{a}$ | 5.53±7.75a | 106.5±32.0$^{a}$ | 229.2±51.7$^{a}$ | 47.2±12.3$^{a}$ |
| 10 Female | 1 | 677±110$^{ab}$ | 42.04±9.14$^{a}$ | 48.61±9.12$^{a}$ | -97±238$^{a}$ | 29.52±7.39$^{a}$ | 132.5±30.5$^{a}$ | 279.1±49.3$^{a}$ | 76.1±11.7$^{a}$ |
| 10 Male | 2 | 375.0±87.1$^{b}$ | 28.91±7.22$^{a}$ | 39.72±7.20$^{a}$ | 543±188$^{a}$ | 20.94±5.83$^{a}$ | 67.4±24.1$^{a}$ | 200.9±38.9$^{a}$ | 86.94±9.26$^{a}$ |

*N = Number of records, DP = dam parity, KS = kid sex, LMY = lactation milk yield, LPY = lactation protein yield, LFY = lactation fat yield, SCC = somatic cell count, MUN = milk urea nitrogen, LI = lactation index, LVI = lactation value index, MP = milk persistency, DL = dam longevity. Means with different superscripts within a column are significantly different at P<0.05.*

Table 3. 9: Effect of kid sexXanimal birth status on milk production and dairy value traits of Toggenburg goats in South Africa.

| | **Kid sex x Animal birth status** | | | | | |
|---|---|---|---|---|---|---|
| | Female 1 | Female 2 | Female 3 | Male 1 | Male 2 | Male 3 |
| **N** | 259 | 316 | 126 | 65 | 124 | 47 |
| **Traits** | | | | | | |
| **Milk Production** | | | | | | |
| LMY | 657.1±52.9$^{a}$ | 651.1±52.8$^{a}$ | 654.6±52.8$^{a}$ | 603.6±55.5$^{a}$ | 598.2±55.2$^{a}$ | 619.0±54.3$^{a}$ |
| LPY | 38.23±4.39$^{a}$ | 38.23±4.38$^{a}$ | 39.86±4.86$^{a}$ | 35.29±4.60$^{a}$ | 36.63±4.58$^{a}$ | 36.48±4.50$^{a}$ |
| LFY | 45.87±4.38$^{a}$ | 44.07±4.36$^{a}$ | 45.49±4.36$^{a}$ | 41.12±4.59$^{a}$ | 41.45±4.57$^{a}$ | 43.87±4.49$^{a}$ |
| SCC | 183±114$^{a}$ | 188±114$^{a}$ | 176±114$^{a}$ | 299±120$^{a}$ | 294±119a | 321±117a |
| MUN | 22.74±3.55$^{ab}$ | 21.41±3.54$^{b}$ | 24.13±3.53$^{a}$ | 18.43±3.72$^{ab}$ | 19.26±3.70$^{ab}$ | 18.88±3.64$^{ab}$ |
| **Dairy value** | | | | | | |
| LI | 117.4±14.6$^{a}$ | 112.7±14.6$^{a}$ | 120.2±14.6$^{a}$ | 94.8±15.3$^{a}$ | 98.5±15.3$^{a}$ | 106.7±15.0$^{a}$ |
| LVI | 229.2±23.7$^{a}$ | 220.8±23.6$^{a}$ | 236.7±23.6$^{a}$ | 222.1±24.8$^{a}$ | 219.1±24.7$^{a}$ | 228.1±24.3$^{a}$ |
| MP | 67.29±5.63$^{a}$ | 65.43±5.62$^{a}$ | 67.27±5.61$^{a}$ | 73.77±5.90$^{a}$ | 71.03±5.88$^{a}$ | 73.88±5.78$^{a}$ |

*N = Number of records, LMY = lactation milk yield, LPY = lactation protein yield, LFY = lactation fat yield, SCC = somatic cell count, MUN = milk urea nitrogen, LI = lactation index, LVI = lactation value index, MP = milk persistency, DL = dam longevity. Means with different superscripts within a row are significantly different at P<0.05.*

### 3.3.8 Correlation effect among milk variables and random factors.

Table 3.10, the correlation table, shows the relationship between the various factors affecting the traits of Toggenburg goats. Notable positive correlations include milk urine nitrogen (MUN) (0.289), which reflects changes in diet or management, and birth year (BY) with ease of kidding (KE) (0.258), which suggests easier kidding over time, possibly due to improved breeding and care procedures. Longer lactations result in better overall milk yield and value, as evidenced by the strong positive correlation between lactation milk yield (LMY) and lactation length (LL) (0.961) and lactation value (LV) (0.952). On the other hand, there appears to be some environmental influence on lactation length, as seen by the slight negative correlation (-0.077) between LL and AEZ. Seasonal effects on reproduction and birth outcomes are suggested by the moderately favourable associations that the Kidding Season (KS) and Kidding Ease (KE) exhibit with litter size (LS). Improvements in udder health over time are shown by negative correlations between the Somatic Cell Count (SCC) and the birth year (-0.178). Furthermore, there is a significant correlation between persistency (MP) and lactation length (LL) (0.194), suggesting steady milk production at extended lactation times.

Table 3. 10: Pearson correlation co-efficient of milk variables and random factors affecting Toggenburg dairy goats.

| | **AS** | **DP** | **DA** | **BY** | **AEZ** | **KE** | **KS** | **LS** | **A_BSTAT** | **LL** | **LMY (kgs)** | **LFY (%)** | **LPY (%)** | **DW (kg)** | **MP** | **SCC** | **MUN** | **LI** | **LV** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **DP** | -0.093* | | | | | | | | | | | | | | | | | | |
| **D A** | -0.120 * | 0.608 * | | | | | | | | | | | | | | | | | |
| **B Y** | 0.229* | -0.225* | -0.226* | | | | | | | | | | | | | | | | |
| **AEZ** | 0.118* | 0.065* | -0.039 ns | -0.010 ns | | | | | | | | | | | | | | | |
| **K E** | 0.029 $^{ns}$ | -0.048* | -0.054* | 0.258* | 0.058* | | | | | | | | | | | | | | |
| **K S** | 0.081* | 0.087* | 0.073* | 0.141* | 0.203* | 0.264* | | | | | | | | | | | | | |
| **LS** | 0.058* | 0.031 $^{ns}$ | 0.016 ns | 0.350* | -0.021 ns | 0.168* | -0.039 ns | | | | | | | | | | | | |
| **A_BSTAT** | 0.396* | -0.053* | -0.004 ns | 0.143* | 0.252* | 0.079* | 0.138* | 0.049* | | | | | | | | | | | |
| **LL** | 0.029 $^{ns}$ | -0.056* | -0.075* | 0.204* | -0.077* | 0.042* | -0.172* | 0.153* | 0.039 $^{ns}$ | | | | | | | | | | |
| **LMY (kgs)** | 0.026 $^{ns}$ | -0.048* | -0.074* | 0.218* | -0.072* | 0.056* | -0.170* | 0.165* | 0.040 $^{ns}$ | 0.961* | | | | | | | | | |
| **LFY (%)** | 0.019 $^{ns}$ | 0.036 $^{ns}$ | 0.034 ns | 0.042* | 0.005 ns | 0.037 $^{ns}$ | -0.003 ns | 0.029 ns | -0.022 $^{ns}$ | -0.146* | -0.075* | | | | | | | | |
| **LPY (%)** | -0.026 ns | 0.003 $^{ns}$ | 0.019 ns | -0.093* | -0.067* | -0.100* | 0.026 $^{ns}$ | -0.031 ns | -0.016 $^{ns}$ | -0.156* | -0.096* | -0.066* | | | | | | | |
| **D W (kg)** | 0.033 $^{ns}$ | -0.004 ns | -0.019 ns | 0.007 ns | 0.080* | -0.034 ns | -0.133* | 0.024 ns | 0.007 $^{ns}$ | 0.073* | 0.100* | 0.106* | 0.058* | | | | | | |
| **MP** | 0.048* | -0.056* | -0.082* | 0.165* | 0.004 ns | -0.006 ns | -0.072* | 0.059* | 0.035 $^{ns}$ | 0.194* | 0.181* | -0.003 $^{ns}$ | -0.030 ns | 0.135* | | | | | |
| **SCC AVG (x1000 c** | -0.007 ns | 0.002 $^{ns}$ | 0.015 ns | -0.178* | 0.035 ns | -0.079* | 0.043* | -0.098* | -0.045* | -0.158* | -0.155* | 0.007 $^{ns}$ | 0.049* | -0.087* | -0.024 ns | | | | |
| **MUN** | 0.117* | -0.024 ns | -0.011 ns | 0.289* | -0.086* | -0.023 ns | -0.088* | 0.094* | 0.017 $^{ns}$ | 0.072* | 0.073* | 0.052* | 0.139* | 0.052* | 0.170* | 0.017 ns | | | |
| **L I** | -0.038 ns | 0.032 $^{ns}$ | 0.045 ns | -0.054* | -0.062* | -0.013 ns | 0.104* | -0.025 ns | -0.041 $^{ns}$ | -0.334* | -0.231* | 0.600* | 0.506* | -0.433* | -0.126* | 0.102* | 0.083* | | |
| **L V** | 0.040* | -0.058* | -0.080* | 0.241* | -0.086* | 0.040 $^{ns}$ | -0.174* | 0.167* | 0.048* | 0.952* | 0.953* | 0.013 $^{ns}$ | 0.002 $^{ns}$ | 0.120* | 0.327* | -0.154* | 0.140* | -0.152* | |
| **DL (years** | 0.070 $^{ns}$ | 0.172* | 0.093* | -0.401* | 0.162* | -0.130* | 0.086* | -0.033 ns | 0.076* | -0.046 ns | -0.044 $^{ns}$ | -0.025 $^{ns}$ | -0.023 ns | 0.027 $^{ns}$ | -0.005 ns | 0.096* | -0.132* | -0.034 ns | -0.051 ns |

*AS= genotype codes, DP = Dam parity, DA = Dam age, AEZ = Ago-ecological zone codes, BY = Birth year, KE = Kidding ease, KS = Kid status, LS = Litter size, A_BSTAT = Animal birth status, LL = lactation length, LI = lactation index, LMY = Lactation milk yield, LFY = Lactation fat yield, LPY = Lactation protein yield, DW = Dam weight, MUN = milk urea nitrogen, LI = lactation index, LV = lactation value, DL = longevity, *: significant different at p<0.05,* $^{ns}$*: not significant.*

## 3.4 Discussion

### 3.4.1 Effect of environmental factors on reproductive, milk production, and dairy value traits.

The research indicated that the kidding season has a notable impact on kid status and somatic cell count (SCC). Kids born in winter showed better survival rates, attributed to favourable weather and better nutritional resources. This supports findings from Homesteader (2024) and Danso *et al.* (2024), who emphasised the advantages of milder seasons in alleviating heat stress. On the contrary, the study found an increase in SCC during spring, indicating a higher likelihood of udder infections, likely due to variable temperature and humidity that encourage bacterial growth. This observation is consistent with Olde *et al.* (2007), who noted similar increases in SCC during spring. On the contrary, autumn recorded the lowest levels of SCC, potentially due to stable climatic conditions that support the health of the udder. However, Gayathri *et al.* (2024) reported no significant seasonal variations in kid status and SCC among Alpine goats, suggesting that breed-specific and regional factors may influence these results.

The study also highlighted the significant effects of agroecological zones on reproductive and milk production traits in Toggenburg goats. Semi-arid regions offered favourable kidding conditions due to lower humidity and drier climates, contrasting with the challenges faced in arid areas where high temperatures and limited feed are prevalent. However, Toggenburg goats demonstrated better kid survival rates in arid conditions, aligning with Dida (2021), who emphasised the importance of effective management to improve the kid viability in such environments. Additionally, the largest litter sizes were recorded in arid zones, indicating that Toggenburg goats can maintain reproductive efficiency in that zone. On the contrary, the highest lactation milk yield was observed in temperate zones, where stable and cooler temperatures improve milk production and pasture quality, as supported by Vroege *et al.* (2023). However, Syrstad (2024) reported significantly lower milk yields in tropical regions, highlighting the influence of temperature and forage availability on dairy productivity.

Milk composition and udder health were also affected by agroecological zones; semi-arid conditions promoted higher lactation fat output and lower SCC levels, suggesting better udder health. These findings align with those of Qiu *et al.* (2022), who linked lower levels of SCC in drier areas with reduced bacterial loads and humidity. In contrast, Alhussien and Dang (2018) found increased SCC levels in humid environments, emphasising the need for environmental management to ensure milk quality. The sub-humid zone exhibited the highest levels of milk urea nitrogen (MUN), probably due to increased protein intake and superior forage quality, as noted by Coop (2024). In general, the semi-arid zone emerged as an ideal environment for Toggenburg goats, balancing favourable kidding conditions, increased milk fat yield, higher MUN levels, and reduced SCC, indicating their adaptability for both reproduction and milk production in this zone.

### 3.4.2 Effect of animal factors on reproductive, milk production, and dairy value traits.

The results of this study illustrate the impact of genotype on reproductive and milk production traits in Toggenburg goats. Goats from the Stud Book Proper showed a higher birth status, indicating enhanced maternal care and genetic benefits, as noted by Gregory (2009). Although the foundation stock (F0) animals had higher baseline milk yields, research suggests that advanced genotypes such as Appendix B may exceed the foundation stock in milk production when optimally managed (Miglior *et al.,* 2017; Galukande *et al.,* 2013). Furthermore, increased levels of milk urea nitrogen (MUN) in F0 animals indicate efficient nitrogen metabolism, potentially linked to dietary intake or genetic adaptation (Penn State Extension, 2016; Souza *et al.,* 2021). However, the lack of significant differences in litter size and age at first kidding among genotypes implies that environmental and management factors may play a more crucial role in these traits than genetic makeup alone (Norberg *et al.,* 2019; Selvaggi *et al.,* 2017). Dam parity significantly influenced reproductive and milk production traits, particularly in terms of litter size and lactation protein yield. Parities 2 to 5 yielded the largest litters, suggesting that this stage represents optimal reproductive performance, consistent with earlier studies (Crepaldi *et al.,* 1999; Agnihotri and Rajkumar, 2007). First-parity dams typically produced smaller litters due to ongoing physiological growth (Stewart, 2021). However, an observable decline in lactation protein yield was observed as parity increased, especially in parities 7 to 10, confirming findings that suggest ageing affects protein synthesis capacity (Margetínová *et al.,* 2003). In particular, parity 10 demonstrated the highest milk persistence, supporting Salama *et al.* (2005), who proposed that older dams can maintain more consistent milk production throughout lactation despite lower peak yields. On the contrary, Bobadilla *et al.* (2024) indicated that younger parity dams experience greater variability in milk production, likely due to hormonal fluctuations. Kid sex, litter size, and birth status did not significantly influence milk production traits, reinforcing previous findings that the physiological mechanisms governing milk synthesis are largely independent of offspring characteristics (Pérez-Barbería *et al.,* 2022; Pillay and Davis, 2023). Despite variations in litter size, adaptations in the mammary glands seem to effectively regulate milk yield and composition, as suggested by Zamuner *et al.* (2020). Similarly, birth status did not have a noticeable effect on milk fat and protein content, corroborating previous research that indicates that these components remain stable under different birth conditions (Goetsch *et al.,* 2011; Bhinder *et al.,* 2023). These findings underscore the importance of genetic selection, environmental adaptation, and management practices in enhancing dairy goat productivity beyond offspring-related factors alone.

### 3.4.3 Effect of Genotype-by-environmental (GXE) interactions on reproductive, milk production, and dairy value.

#### 3.4.3.1 Genotype x kid sex, AEZs X kid sex and litter size, kid sex X litter size, and litter size X animal birth status

The results of the current study are consistent with research by Taiwo Idowu and Olufunke Adewumi (2017) and Markovic *et al.* (2019), who noted that although genetic variations are important for milk production and quality, kid sex is not a significant determinant. This highlights the greater influence of environmental factors and management techniques on lactation outcomes. Furthermore, Mpofu *et al.* (2016) and Bedada et al. (2021) pointed out that while agro-ecological zones significantly impact feed availability and overall management practices, they have no direct effect on milk production based on the sex of the kids. However, the study by Kobek-Kjeldager *et al.* (2019) found that although environmental factors affect survival rates and growth performance, they do not substantially interact with litter size to affect milk production traits. On the contrary, the Committee on Technological Options to Improve the Nutritional Attributes of Animal Products (2016) observed that, in their study of dairy goats under various management systems, the sex of the offspring did not significantly affect the composition or production of milk, even if the size of the litter may increase the nutritional demands of the dam. Zamuner *et al.* (2020) also found that although birth circumstances and litter size may affect offspring health during kidding, they have no discernible effect on the amount or makeup of milk produced by dairy goats.

#### 3.4.3.2 Dam parity x kid sex

The pattern observed in the current study is consistent with research by Carnicella *et al.* (2008) and Flores-Najera *et al.* (2021), who noted that both the sex of the offspring and parity can influence lactation yield in dairy goats. Specifically, in earlier parities, male offspring tend to drive higher milk production due to their higher nutrient demands. Similarly, Barsila (2019) highlighted that the effects of parity are more pronounced in milk production but not necessarily in compositional qualities such as protein and fat content. However, Carnicella *et al.* (2008) found no significant differences in milk yield associated with kid sex across different parities, indicating that while parity affects lactation performance, the impact of kid sex remains variable. This suggests that other environmental and management factors may also play a role, although parity-by-sex interactions could have some influence.

#### 3.4.3.6 Kid sex x animal birth status

The findings of the current study are consistent with those of Juncker *et al.* (2023), who observed that while birth complications can induce stress in the dam and lead to variations in milk composition, the sex of the offspring does not significantly affect the overall characteristics of milk production. Similarly, Santos *et al.* (2014) noted that challenging deliveries in dairy goats could result in increased milk urea nitrogen (MUN), which is often indicative of protein catabolism and metabolic stress. However, Beatson *et al.* (2019) found that although birth status influenced MUN levels, other traits of milk production were not consistently altered by the relationship with kid sex. This suggests that the physical stress associated with kidding is more directly related to its impact on milk urea nitrogen than the sex of the kid.

## 3.5 Conclusion and Recommendations.

### 3.5.1 Conclusion

In conclusion, this study offers a detailed examination of the different factors that influence the milk production traits of South African Toggenburg dairy goats.

There is a need to further explore the phenotypic plasticity of Toggenburg blood purity levels based on the classification of F0, CP, A, B, and SP in various agro-ecological zones characterised by different geographic locations, edaphic and climatic factors of South Africa.

Winter-born kids are generally healthier, although spring-produced milk has higher somatic cell counts, indicating lower quality. Higher milk urea nitrogen and fat outputs, as well as reduced somatic cell counts, make kidding easier in semi-arid zones. While temperate zones produce more milk, arid zones produce more kids. Although foundation stock animals produce more milk and milk urea nitrogen, StudBook proper and Appendix A animals have easier kidding and healthier kids. Multiple births are more common between parities 1 and 7; however, protein output declines between parities 7 and 10, with parity 10 being optimal for milk persistence. The number, sex, or birth status of the offspring generally does not impact the quantity or quality of milk produced in Toggenburg goats. Male kids produce more milk in parities 2, 3, and 5, while female kids produce more milk in parities 4 and 6. However, those with difficult births tend to have higher milk urea nitrogen levels, but agro-ecological zones, kid sex, and litter size generally do not affect milk production and quality.

In this study, purposive sampling, a non-probability method where researchers deliberately choose participants based on particular traits important to the research, was also employed. Specifically, Toggenburg genotypes and agro-ecological zones with sufficient performance data were selected to enable a robust analysis of phenotypic plasticity.

### 3.5.2 Recommendations

Farmers and breeders are recommended to plan kidding in winter to improve kid health and focus efforts on milk production in temperate zones for optimal yield. Breeding Appendix A and StudBook Proper animals may enhance kidding ease and kid health, while foundation stock animals can be prioritised for higher milk yield. Goats should be kept to at least parity 10 for long-term milk persistence, as this stage promotes more consistent milk production throughout the lactation period.

However, as noted, the study acknowledges a gap in addressing how these traits respond to varying agro-ecological conditions or how the phenotypic plasticity of different Toggenburg goat blood purity levels contribute to performance variation.

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# CHAPTER 4

# PHENOTYPIC PLASTICITY IN DAIRY PRODUCTION TRAITS OF TOGGENBURG GOAT GENOTYPES ACROSS SOUTH AFRICAN AGRO-ECOLOGICAL ZONES

## Abstract

The study aimed to evaluate the phenotypic plasticity in reproductive and milk production traits of Toggenburg blood purity levels across different South African agro-ecological zones using reaction norm models and other methods. The study was carried out using a longitudinal observational design. Performance records of 2417 does across five agro-ecological zones: arid (A), semi-arid (SA), sub-humid (SH), humid (H) and temperate (T) with five Toggenburg blood breed purity: Founders (F0), CP, Appendix A animals (A), Appendix B animals (B), and Studbook proper animals (SP) were obtained from the Milch Breeders Society of South Africa LOGIX database. Descriptive statistics of milk production, reproductive and dairy value traits, and least square means per AEZ and TOG genotype were computed using GLM of Minitab 18.1 software. The four methods of determining Phenotypic Plasticity Index (PPI) were reaction norm-based, infinite-dimensional model, character trait, and variance-based model. The p-value and R2 values were used to assess the significance of estimates and goodness-of-fit for each method, respectively. Data visualisation techniques used included surface plots and phenotypic plasticity trends. The results showed that the variance-based and character trait methods revealed significant phenotypic plasticity *($p<0.05$)* in somatic cell count, kid status score, litter size and kidding ease score in high humidity and low temperature zone.one. Reaction norm analysis also demonstrated significant *($p<0.05$)* plasticity in Kid status score, birth difficulty score, MUN, milk persistence, lactation value index, lactose with $R^2$ of 81.58% milk yield that exhibits a high $R^2$ of 99.64% among blood purity level F0. Regression model analysis confirmed significant *($p<0.05$)* GxE interactions for lactose with $R^2$ of 81.58%, dam longevity (r = 82.57%), milk persistence, birth difficulty score, and kidding ease score. PPI was not significant *($p>0.05$)* across genotypes and AEZ in key traits such as AFK and KI in all methods. Surface plots and phenotypic plasticity trends confirmed the observed results in all traits, with lactation milk yield, prolificacy (litter size), and dam longevity indicating conspicuous phenotypic plasticity. Surface plots and phenotypic plasticity trends confirmed the observed results in all traits. The study highlights the importance of considering genotype-environment interactions in breeding programs for Toggenburg dairy goats. While some traits, such as kid status and lactation milk production, exhibit relatively low phenotypic plasticity, others, such as kidding ease and milk protein production, are significantly influenced by environmental conditions. A change in environmental conditions where a decrease in temperature and an increase in humidity (arid to temperate) indicated significant phenotypic plasticity of TOG blood purities in milk production, reproductive, and dairy value traits. The precision of the estimates was assessed, and the ideal method to assess phenotypic plasticity is the reaction norm-based method.

**Keywords**: Studbook Proper, dairy value traits, decreasing temperature, increasing humidity, breed purity.

## 4.1 Introduction

Through selective breeding programs, dairy goat stud breeding focuses on improving traits such as conformation, health, and milk yield to provide superior breeding stock for improved herd productivity (Gipson, 2019; Tranel *et al.,* 2020). This is vital for commercial farms, as maintaining profitable milk yield and quality is the key to their success (Dairy Goat Production, 2022). Breeds such as Toggenburg, Saanen and Nubian are popular in the industry for their adaptability and excellent milk production (Dairy Goat Production, 2022). Toggenburg goats, in particular, are known for their resilience and ability to produce milk under challenging conditions, making them highly adaptable to diverse environments (LRRD, 2014). Dairy goat production benefits commercial and small-scale farms by generating revenue from fresh milk and value-added products such as cheese, yoghurt and goat milk soap (Miller and Lu, 2019). Goat milk is a staple in many low-income countries due to its accessibility and health advantages, such as easier digestion compared to cow milk, due to its smaller fat globules and unique protein composition (ALKaisy *et al.,* 2023; Gomes and Pereira, 2019). Additionally, the versatility of goat milk enhances its marketability and improves producer profitability (Future Market Insights, 2023).

Genetic factors strongly influence goat milk production and reproductive efficiency (Luo *et al.,* 2019). In breeds such as Toggenburg and other European goats, certain genes linked to milk production and adaptation suggest that genetic selection can enhance traits such as heat tolerance and milk production (Ghanatsaman *et al.,* 2023). These genetic factors are crucial for breeding programs aimed at optimising goat performance in different environments. Environmental factors also play an important role. The soil composition affects the nutritional quality of the feed, which influences goat nutrition and productivity (Furtak and Gałązka, 2019). The mineral content in the soil impacts the nutritional value of pasture, affecting both milk production and reproductive efficiency. Additionally, climate factors such as temperature and rainfall patterns influence feed availability, which in turn affects lactation periods and reproductive cycles (Godde *et al.,* 2021). Adaptations to these environmental variations are essential for maintaining consistent productivity across agro-ecological zones. Management practices, including feeding strategies, breeding methods, and herd management, also significantly impact milk production and reproduction (Fodor *et al.,* 2018). Although intensive systems may boost production, they require more resources, whereas extensive systems rely on natural adaptation to local conditions (Wikipedia Contributors, 2019). Understanding the interactions between genetics, environment, and management is key to improving dairy goat production in diverse agro-ecological zones (Nguluma *et al.,* 2022).

Understanding how Toggenburg goats adapt to different environments is essential, motivating the study of genotype-by-environment (GxE) interactions and phenotypic plasticity in these animals (Christensen *et al.,* 2021). GxE interactions, which reflect how genotypes respond differently to varying environmental conditions, significantly affect traits such as growth, reproduction, and milk production (Sartori *et al.,* 2022). This emphasises the need to consider both environmental and genetic factors when assessing livestock performance. Phenotypic plasticity, the ability of animals to produce different traits in response to environmental changes, is closely related to GxE interactions (Sommer, 2020). In dairy goats, it helps identify genotypes that are more resilient and better suited to specific climates and management systems, which is crucial for improving sustainability and productivity in different agro-ecological zones (Wang *et al.,* 2023; Zhang *et al.,* 2022; Vastolo *et al.,* 2024). Despite its importance, the phenotypic plasticity of Toggenburg goats has not been studied in South Africa, creating a knowledge gap that limits the development of locally tailored breeding programs. Reaction norm models are valuable tools for studying GxE interactions, providing accurate predictions of genotype performance across environments (Dekkers, 2021; Waters *et al.,* 2024; Zefreh *et al.,* 2023). These models help breeders optimise productivity and adaptability to diverse conditions (Diouf et al., 2020). By focusing on GxE interactions and phenotypic plasticity, this study aims to improve breeding strategies, enhance economic sustainability, and adapt Toggenburg goat farming to carious agro-ecological zones of South African. Therefore, the study aimed to evaluate the phenotypic plasticity of different Toggenburg goat genotypes in relation to milk production performance across agro-ecological zones.

## 4.2 Methodology and Analytical Procedures

### 4.2.1 Study site, animals, and management

The study site, animals, and management follow the description outlined under Chapter 3.2.1 and 3.2.2

### 4.2.2 Study design, data collection, and data editing.

#### 4.2.2.1 Study design, sampling and data collection

The study used a longitudinal observational design to evaluate the phenotypic plasticity of Toggenburg goat blood purity levels (F0, CP, B, A, and SP) in different AEZ (arid to temperate: increasing humidity and reducing temperature) of South Africa. Performance records from 17 farms (n= 2 417 does) obtained from the LOGIX database of the Milch Breeders Society of South Africa were used. The selected farms were purposively selected to ensure representation across all five AEZs based on climatic conditions, vegetation types, and geographic regions. A description of the AEZ is under Chapter 3 Section 3.2.1. Environmental variables such as average annual temperature, annual rainfall, humidity levels, and vegetation types were collected for each zone. Farms with incomplete or inconsistent data, such as missing birth dates, lactation records, or reproductive history, were excluded to maintain data integrity. Additionally, farms that did not follow standardised recording procedures or lacked sufficient historical data for longitudinal analysis were also excluded. The sample size of the does was determined by the availability of comprehensive performance records from the participating farms. Although the distribution of does vary across zones, the inclusion of farms from all AEZs ensured a broad representation of environmental influence on Toggenburg goat performance. The final sample size provided sufficient data for the statistical analysis of phenotypic plasticity.

#### 4.2.2.2 Data editing

Using Microsoft Excel, important factors such kid sex, litter size, season of birth, year of birth, sire ID, dam ID, breeder, farm, kidding interval, kidding season, and agro-ecological zones were identified and captured.

### 4.2.3 Data analysis

Minitab 18.1 (2017) statistical software was used for all the analyses.

Determination of phenotypic plasticity index:

a. Linear regression model/infinite-dimensional model (Jamrozik and Schaeffer, 1997; Wilson et al., 2005)

This model makes the assumptions that genotypes respond predictably and that environmental influences are constant. By considering environmental variation as an infinite-dimensional function, the infinite-dimensional model was expanded beyond linear regression.

Procedure:

The phenotype $y$ is modelled as a function of environmental conditions $E$.

Linear regression: $yi = \beta 0 + \beta 1Ei + \varepsilon i$

where:

$yi$ = observed phenotype for individual i.

$Ei$ = environmental factors (AEZs: arid, semi-arid, sub-humid, humid, temperate)

$\beta 0$ = intercept

$\beta 1$ = slope (measuring the rate of trait change per unit environment)

$\varepsilon i$ = residual error

Expanded to infinite-Dimensional model to allow non-linear, complex trait responses to environmental variation.

$yi = \int \beta(E)\ Ei\ dE + \varepsilon i$

b. Reaction norm model (Gautier and Naves, 2011; Kelly *et al.,* 2012)

A reaction norm explains how the phenotype of a genotype varies in various environments.

Procedure:

A reaction norm model (Su *et al.* 2006) in Minitab 18.1 (2017) statistical software was employed as follows:

$Pi = \beta 0 + \beta 1Ei + \beta 2Gi + \beta 3Gi\text{x}Ei + \varepsilon i$

Where:

$Pi$ = dependent variable (reproductive, milk production, dairy value)

$\beta 0$ = Intercept (population mean assuming constant lactation length, dam parity, dam age, dam weight)

$\beta 1$, $\beta 2$, and $\beta 3$ = are coefficients representing the linear effects of genotype, agro-ecological zone, and interaction effect, respectively.

Ei = Environmental sensitivity representing the agro-ecological zone (coded as arid = 1, semi-arid = 2, sub-humid = 3, humid = 4, temperate = 5).

Gi = Blood breed purity level effects (F0, CP, A, B, and SP)

GixEi = Genotype-environment interaction coefficient

$\varepsilon i$ = Residual error assumed to be normally distributed with mean 0 and constant variance

To visualize reaction norms, 3D Surface plots were used to visualize the relationship between two independent variables (genotype and environment) and one dependent variable at a time (e.g., phenotype). The surface plot equation was represented as:

$z = f(x, y) = \beta 0 + \beta 1x + \beta 2y + \beta 3xy + \varepsilon$

Where:

$z$ = Phenotype (dependent variable)

$x$ = Environment (independent variable)

$y$ = Genotype (independent variable)

$\beta 0$ = Intercept

$\beta 1$ = Environmental sensitivity

$\beta 2$ = Genotypic effect

$\beta 3$ = Genotype-environment interaction coefficient

$\varepsilon$ = Residual error assumed to be normally distributed with mean 0 and constant variance

c. Character trait model/coefficient of variation (CV) (De jong and Bijma, 2002; Murren *et al.,* 2015)

In contrast to a continuous function, this model views the reaction norm as a collection of distinct, connected characteristics. Every phenotype unique to a given environment was represented as a distinct trait.

Procedure:

A multi-trait model was applied as:

$y = Xb + Zu + e$

Xb = fixed effects

Xu = random genetic effects

e = residuals

CV = Standard deviation (SD)/mean traits ($\bar{x}$)*100

d. Variance-based model (Rauw and Gomez-Raya, 2015; Sommer, 2020; Rovelli *et al.,* 2020)

The main focus of this model is how environmental variations in trait variance occur. It aids in determining sensitivity to the environment.

Procedure:

Total variance (VP) was decomposed as follows:

VP = VG + VE + VGxE

Where:

VG = genetic variance

VE = environmental variance

VGxE = interaction variance

## 4.3 Results

### 4.3.1 Descriptive statistics of study variables.

Table 4.1 provides descriptive statistics of study variable of Stud Toggenburg goats. The larger mean values represent desirable outcome for a trait. Higher SE mean shows more uncertainty around whether the sample mean accurately represents the population mean. Higher SD represents more variability among individual goats. Higher CV value indicates more variation in that trait relative to the mean. Minimum and maximum values represent the range, showing the lowest and highest observations for each variable.

Table 4. 1: Descriptive statistics of study variables of stud TOG goats' responses to different agro-ecological zones.

| Variable | N | Mean | SE Mean | SD | CV (%) |
|---|---|---|---|---|---|
| Dam age (months) | 1657 | 74.644 | 0.868 | 35.347 | 17.35 |
| Kidding ease Score | 2417 | 0.4617 | 0.0132 | 0.6506 | 14.91 |
| Kid status | 2417 | 0.6045 | 0.0116 | 0.5682 | 23.99 |
| Litter size/ Prolificacy | 2417 | 1.7609 | 0.0132 | 0.6478 | 16.79 |
| Kidding difficulty score | 2417 | 1.5784 | 0.0143 | 0.7022 | 14.49 |
| Lactation length (in days) | 2417 | 190.17 | 2.36 | 116.26 | 21.13 |
| LMY (kgs) | 2417 | 635.94 | 7.62 | 374.40 | 18.87 |
| LFY (%) | 2417 | 39.504 | 0.168 | 8.257 | 20.90 |
| LPY (%) | 2417 | 34.749 | 0.170 | 8.362 | 24.07 |
| Dam weight (kg) | 2417 | 54.786 | 0.242 | 11.882 | 21.69 |
| SCC avg (x1000 cells/ml) | 2417 | 386.73 | 4.52 | 222.18 | 27.45 |
| Milk urea nitrogen (mg/dL) | 2417 | 21.903 | 0.152 | 7.473 | 24.12 |
| Lactation index | 2417 | 90.043 | 0.650 | 31.951 | 15.48 |
| Lactation value index | 2417 | 229.05 | 2.92 | 143.66 | 12.72 |
| Longevity (months) | 754 | 86.55 | 1.90 | 52.13 | 20.23 |
| Longevity (years) | 754 | 7.114 | 0.156 | 4.285 | 20.23 |
| Milk persistency (%) | 2417 | 74.278 | 0.221 | 10.883 | 14.65 |

*N: population size, SE mean: standard error of the mean, SD: standard deviation, CV: coefficient of variance, LMY: lactation milk yield, LFY: lactation fat yield, LPY: lactation protein yield, SCC avg: somatic cell count average.*

### 4.3.2 Significant factors affecting reproductive, milk production, and dairy value traits

The significant factors that were adjusted for during the determination of phenotypic plasticity index (PPI) are represented on table 4.2.

Table 4. 2 Adjusted significant factors during determination of PPI

| **Trait** | **AEZ** | **TOG Genotype** | **Birth Season** | **Birth Year** | **Dam Parity** | **Breeder/ Farm** | **Kidding Season** |
|---|---|---|---|---|---|---|---|

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| *Milk production traits* | | | | | | | |
| Milk Yield | NS | NS | NS | NS | ** | NS | NS |
| Fat (%) | NS | NS | NS | NS | NS | ** | NS |
| Lactose (%) | NS | - | - | *** | NS | - | NS |
| Protein (%) | ** | NS | NS | ** | ** | ** | NS |
| Somatic Cell Count | NS | NS | NS | *** | NS | * | ** |
| Milk Urea Nitrogen | NS | NS | NS | NS | NS | *** | NS |
| *Reproductive traits* | | | | | | | |
| Kidding Ease Score | ** | NS | NS | *** | NS | *** | NS |
| Kid Status Score | *** | ** | NS | *** | NS | *** | ** |
| Age at First Kidding | *** | NS | *** | *** | - | - | - |
| Kidding Interval | NS | NS | NS | NS | - | - | - |
| Litter Size | *** | NS | NS | *** | *** | *** | NS |
| Birth Difficulty Score | NS | *** | NS | *** | NS | *** | NS |
| *Dairy value traits* | | | | | | | |
| Lactation Index | NS | NS | NS | ** | * | * | NS |
| Lactation Value Index | NS | NS | NS | * | NS | NS | NS |
| Milk Persistency (%) | NS | NS | NS | NS | ** | NS | NS |
| Dam Longevity (years) | NS | NS | NS | *** | NS | NS | NS |

*NS = Not significant (P>0.10), * = significant at p<0.10, ** = significant at p<0.05, *** = significant at p<0.001*

### 4.3.3 Assessment of phenotypic plasticity index using different methods

The tables present a phenotypic plasticity index analysis to assess phenotypic plasticity in Toggenburg goats in South Africa. The models examined the effects of blood purity levels, AEZs, and their interactions on various traits of milk production, reproductive, and milk value.

#### 4.3.3.1 Variance-based and Coefficient of variance method (CV)

Table 4.2 presents the variation and the coefficient of variation (CV) for the traits studied. Significant plasticity *(p<0.05)* was observed for somatic cell count, kid status score, litter size, and kidding ease score, suggesting that these traits are highly influenced by environmental factors. The temperate zone exhibited the highest CV for SCC, indicating substantial sensitivity to environmental conditions. Kid status score did not show variation in the arid, semi-arid, and semi-humid zones; however, it showed the highest plasticity in the temperate zone, highlighting its environmental dependence. Similarly, litter size exhibited a higher CV in the semi-humid and temperate zones. Kidding ease score did not show variation in the arid, semi-arid and semi-humid zones but increased significantly in the humid and temperate zones. On the contrary, the percentage of fat, milk production, the percentage of lactose, the percentage of protein, the nitrogen of milk urea nitrogen, kidding interval, age at first kidding, birth difficulty score, lactation index, lactation value index, milk persistency, and dam longevity showed no significant plasticity *($p>0.05$),* indicating relative stability in the agroecological zones. However, some of these traits exhibited variation between zones. Milk persistence showed the highest CV in the temperate zone, while dam longevity demonstrated a greater variation in the arid zone.

#### 4.3.3.2 Reaction norm-based method

Table 4.3 presents a reaction norm analysis. This analysis revealed significant phenotypic plasticity in several traits of Toggenburg goats, particularly with regard to reproductive performance and dairy value. In particular, the percentage of lactose percentage ($R^2$ = 81.58%), kidding ease score ($R^2$ = 65.04%), and kid status score ($R^2$ = 63.81%) exhibited significant *($p<0.05$)* phenotypic plasticity, indicating strong environmental influences on these traits. Additionally, lactation index, lactation value index, and milk persistency also demonstrated significant *($p<0.05$)* phenotypic plasticity. Milk yield ($R^2$ = 99.64%) and milk urea nitrogen ($R^2$ = 48.59%) showed significant *($p<0.05$)* phenotypic plasticity as well. Another reproductive trait, birth difficulty score ($R^2$ = 27.11%), also exhibited significant *($p<0.05$)* phenotypic plasticity. In contrast, fat percentage, protein percentage, somatic cell count, age at first kidding, kidding interval, and litter size all indicated no significant *($p>0.05$)* phenotypic plasticity for these traits. This implies that the relationship between genotype and phenotype is not significantly altered by environmental variation for these traits.

#### 4.3.2.3 Regression-based method

Table 4.4 presents the results of a regression model analysis. SCC exhibited significant *($p<0.05$)* phenotypic plasticity, with the effect of genotype varying substantially across different agro-ecological zones (AEZs). This suggests that environmental factors within different AEZs influence the expression of genetic potential for SCC. The birth difficulty score also showed a statistically significant *($p<0.05$),* albeit weaker, interaction between blood purity levels and AEZ, implying some degree of environmental influence on the genetic predisposition to birth difficulties. Significant phenotypic plasticity *($p<0.05$)* was also observed in milk persistence, suggesting that the combined effect of genotype and AEZ contributes to variation in milk persistence. Similar to somatic cell count, dam longevity exhibited a significant *($p<0.05$)* interaction between genotype and AEZ, indicating that environmental factors within different AEZs influence the expression of genetic potential for dam longevity. For traits such as milk yield, fat content, lactose content, protein content, milk urea nitrogen, kidding ease score, kid status score, age at first kidding, kidding interval, litter size, lactation index, and lactation value index, the lack of a significant interaction *($p>0.05$)* suggests that the effects of breed purity on these traits are relatively consistent across the different agro-ecological zones studies.

Table 4. 3: Variance-based and Coefficient of variation method

| | **Phenotypic Plasticity Index** | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **Method** | **Variance-Based Method** | **Coefficient of Variation (CV) Method** | | | | | **p-value** | **$R^2$** |
| *Environment* | | *Arid* | *Semi-Arid* | *Semi-Humid* | *Humid* | *Temperate* | | |
| *Milk production traits* | | | | | | | | |
| Fat (%) | 0.5484 | 10.05 | 20.33 | 8.16 | 16.25 | 19.94 | 0.128 | 79.12 |
| Milk Yield | 394324.2 | 34.91 | 57.58 | 48.84 | 57.46 | 69.66 | 0.770 | 99.64 |
| Lactose (%) | 1.6586 | 6.73 | 7.06 | 4.34 | * | 12.36 | 0.508 | 81.58 |
| Protein (%) | 0.8847 | 8.43 | 10.22 | 8.54 | 745.23 | 15.34 | 0.062 | 81.31 |
| Somatic Cell Count | 929621.7 | 102.34 | 70.15 | 82.12 | * | 94.91 | 0.032 | 35.78 |
| Milk Urea Nitrogen | 29.998 | 12.52 | 12.61 | 22.90 | * | 19.25 | 0.112 | 48.59 |
| *Reproductive traits* | | | | | | | | |
| Kidding Ease Score | 0.3175 | 0.00 | 0.00 | 0.00 | 12.34 | 35.21 | 0.010 | 65.04 |
| Kidding Interval | 1722.85 | 10.37 | 12.19 | 11.88 | * | 12.01 | * | * |
| Age at First Kidding | 1.738 | 10.80 | 10.04 | 7.98 | * | 10.23 | * | * |
| Kid Status Score | 0.1881 | 0.00 | 0.00 | 0.00 | 12.34 | 19.67 | 0.000 | 63.81 |
| Litter Size | 0.5406 | 42.34 | 34.39 | 40.15 | 19.37 | 41.80 | 0.001 | 19.88 |
| Birth Difficulty Score | 0.4926 | 44.76 | 38.79 | 26.82 | 33.08 | 35.93 | 0.073 | 27.11 |
| *Dairy value traits* | | | | | | | | |
| Lactation Index | 1020.575 | 27.21 | 53.82 | 27.23 | * | 29.19 | 0.710 | 61.09 |
| Lactation Value Index | 11760.20 | 65.47 | 64.13 | 76.95 | 65.35 | 78.21 | 0.835 | 46.41 |
| Milk Persistency (%) | 3511.05 | 68.94 | 68.58 | 72.98 | * | 77.13 | 0.058 | 67.17 |
| Dam Longevity (years) | 6.5201 | 69.57 | 39.92 | 40.80 | * | 42.70 | 0.193 | 82.57 |

**: values not computable.*

Table 4. 4: Reaction norm-based method

| | **Phenotypic Plasticity Index** | | | | | | |
|---|---|---|---|---|---|---|---|
| **Method** | **Reaction Norm-based method** | | | | | **p-value** | **$R^2$** |
| *Environment* | *F0* | *CP* | *B* | *A* | *SP* | | |
| *Milk production traits* | | | | | | | |
| Fat (%) | -0.0244 | -0.0307 | -0.0396 | -0.0308 | -0.0345 | 0.419 | 79.12 |
| Milk Yield | 0.1023 | 0.0042 | 0.1452 | -0.0067 | 0.0147 | 0.010 | 99.64 |
| Lactose (%) | 0.0080 | 0.0027 | -0.0123 | 0.0077 | -0.0204 | 0.000 | 81.58 |
| Protein (%) | -0.0088 | -0.0232 | -0.0201 | -0.0135 | -0.0117 | 0.062 | 81.31 |
| Somatic Cell Count | -0.0335 | -0.1117 | 0.0027 | 0.1742 | 0.0806 | 0.929 | 35.78 |
| Milk Urea Nitrogen | 0.0421 | -0.0228 | 0.0089 | 0.0366 | 0.0264 | 0.011 | 48.59 |
| *Reproductive traits* | | | | | | | |
| Kidding Ease Score | -0.0612 | -0.0154 | -0.0187 | -0.0434 | -0.0632 | 0.000 | 65.04 |
| Age at First Kidding | 0.0377 | -0.0047 | -0.0171 | 0.0058 | 0.0022 | 0.708 | 0.05358 |
| Kidding Interval | -0.0248 | -0.0088 | -0.0133 | 0.0019 | -0.0015 | 0.811 | 0.02215 |
| Kid Status Score | -0.0186 | -0.0582 | -0.0199 | -0.0164 | -0.0187 | 0.000 | 63.81 |
| Litter Size | 0.0075 | -0.0892 | -0.0361 | -0.0231 | -0.1203 | 0.439 | 19.88 |
| Birth Difficulty Score | 0.3695 | 0.0.741 | 0.0201 | -0.0201 | -0.0630 | 0.014 | 27.11 |
| *Dairy value traits* | | | | | | | |
| Lactation Index | 0.0632 | -0.0654 | 0.0938 | -0.0218 | 0.0813 | 0.006 | 61.09 |
| Lactation Value Index | 0.0840 | -0.0422 | -0.0794 | -0.0525 | -0.0577 | 0.019 | 46.41 |
| Milk Persistency (%) | -0.0235 | 0.1200 | -0.0094 | 0.0013 | 0.0032 | 0.013 | 67.17 |
| Dam Longevity (years) | -0.0551 | 0.0299 | 0.1070 | 0.0702 | 0.0222 | 0.067 | 82.57 |

Table 4. 5: Regression-based method

| **Trait** | | | **Phenotypic Plasticity Index** | | | |
|---|---|---|---|---|---|---|
| | **Regression-Based Method** | | | | **p-value** | **$R^2$** |
| | Intercept | B1 – Blood breed purity (AS) | B2 - AEZ | Interaction | | |
| *Milk production traits* | | | | | | |
| Milk Yield | 983.6±166.5 | -3.925±59.86 | 32.33±36.15 | -7.711±12.47 | 0.5365 | 79.12 |
| Fat (%) | 4.487±0.1651 | 0.0033±0.0593 | -0.1058±0.0358 | -0.0021±0.0124 | 0.8631 | 99.64 |
| Lactose (%) | 4.193±0.0706 | 0.0469±0.0254 | 0.04249±0.0153 | -0.0128±0.0053 | 0.0154 | 81.58 |
| Protein (%) | 3.492±0.8373 | -0.0645±0.0301 | -0.0634±0.0182 | 0.0054±0.0063 | 0.3886 | 81.31 |
| Somatic Cell Count | 1910±251.4 | -313.2±90.47 | -156.1±56.60 | 55.97±19.19 | 0.0036 | 35.78 |
| Milk Urea Nitrogen | 28.27±1.422 | -0.3262±0.5088 | -0.0505±0.3379 | 0.1479±0.1104 | 0.1808 | 48.59 |
| *Reproductive traits* | | | | | | |
| Kidding Ease Score | 1.893±0.4073 | 0.0423±0.1024 | 0.1072±0.0834 | -0.0423±0.0209 | 0.0437 | 65.04 |
| Kid Status Score | 2.123±0.2755 | -0.0212±0.0693 | -0.1227±0.0563 | 0.0212±0.0141 | 0.1342 | * |
| Age at First Kidding | 13.19±0.5595 | -0.0456±0.1552 | -0.1253±0.1661 | 0.0247±0.0465 | 0.5948 | * |
| Kidding Interval | 370.4±19.25 | -4.733±5.408 | -4.504±5.694 | 1.141±1.617 | 0.4807 | 63.81 |
| Litter Size | 1.476±0.5306 | 0.1176±0.1334 | 0.0769±0.1084 | -0.0286±0.0272 | 0.2932 | 19.88 |
| Birth Difficulty Score | 0.4263±0.8935 | 0.4146±0.2009 | 0.2959±0.1803 | -0.0812±0.0406 | 0.0455 | 27.11 |
| *Dairy value traits* | | | | | | |
| Lactation Index | 80.59±7.927 | 3.509±2.837 | 3.012±1.759 | -0.5084±0.5984 | 0.3958 | 61.09 |
| Lactation Value Index | 176.5±28.34 | 0.7631±10.19 | 0.7632±6.151 | -1.946±2.122 | 0.3593 | 46.41 |
| Milk Persistency (%) | 16.52±15.35 | 13.99±5.514 | 11.06±3.408 | -2.481±1.163 | 0.0332 | 67.17 |
| Dam Longevity (years) | 2.485±1.283 | -0.09272±0.8631 | 0.7894±0.2584 | * | 0.0024 | 82.57 |

**: values not computable*

### 4.3.3 Surface plots of reproductive, milk production, and dairy value traits.

The surface plots show the effect of agro-ecological zones and blood breed purity on Toggenburg traits. Reproductive traits responses: kidding ease, kid status, and prolificacy (litter size) are shown in Figures 4.1, Figure 4.2, and Figure 4.3, respectively. Milk production responses which are lactation milk yield, lactation protein yield, lactation fat yield, somatic cell count, and milk urea nitrogen are shown in figures 4.4, 4.5, 5.6, 4.7, and 4.8, respectively. Consequently, Figures 4.9, 4.10, 4.11, 4.12, and 4.13 represent responses to traits of dairy value (lactation index, lactation value index, milk persistence, dam longevity, and lactation length.

#### 4.3.3.1 Reproductive traits' responses

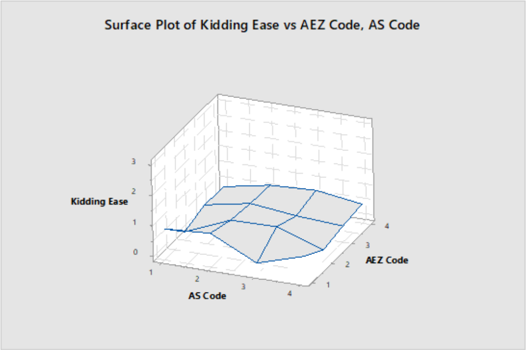


Figure 4. 1 Kidding ease response.

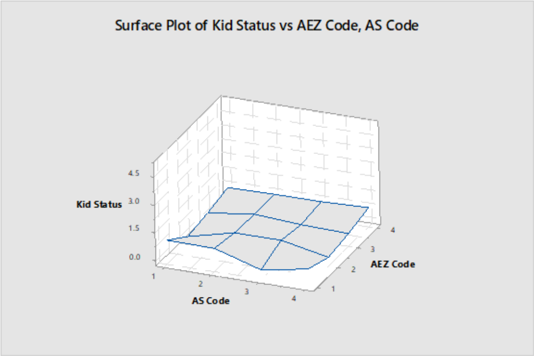


Figure 4. 2 Kid status response.

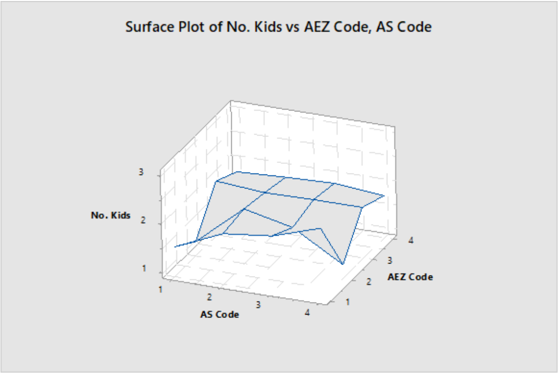


Figure 4. 3 Prolificacy (litter size) response.

### 4.3.3.2 Milk production traits' responses

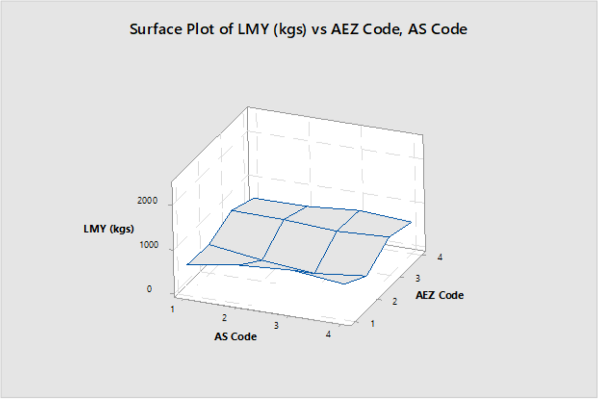


Figure 4. 4 Lactation milk yield response.

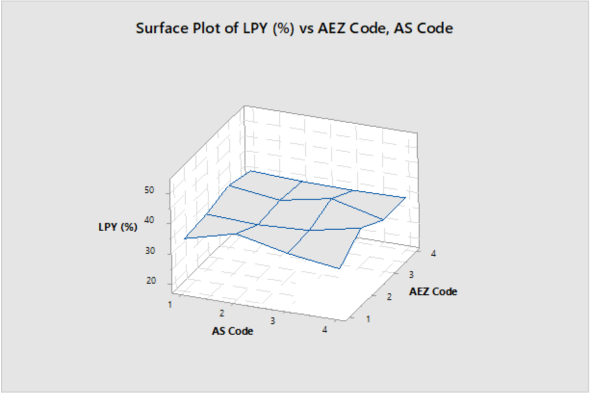


Figure 4. 5 Protein yield response.

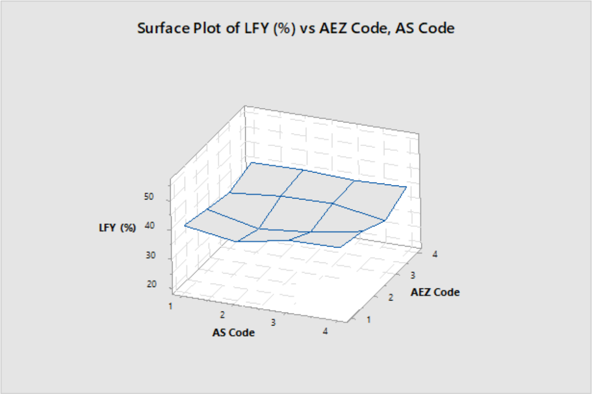


Figure 4. 6 Fat yield response.

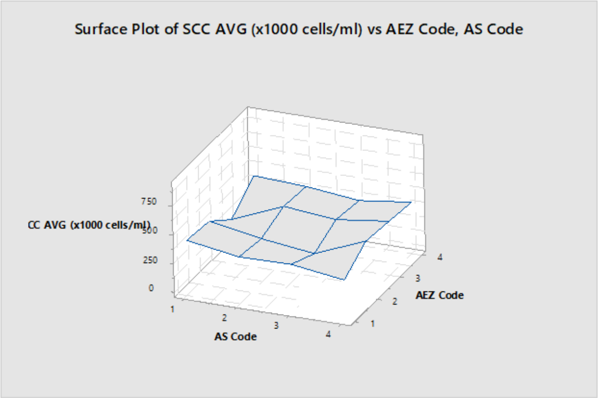


Figure 4. 7 Somatic cell count response.

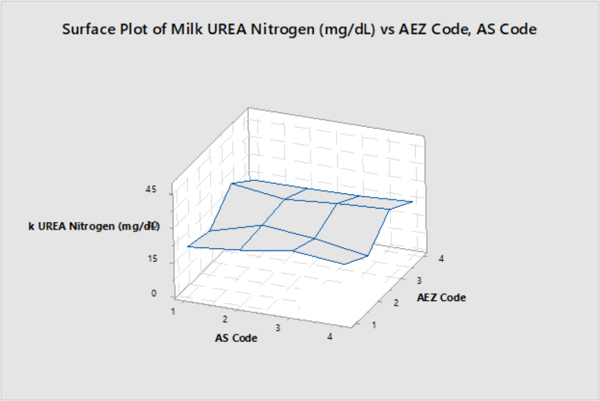
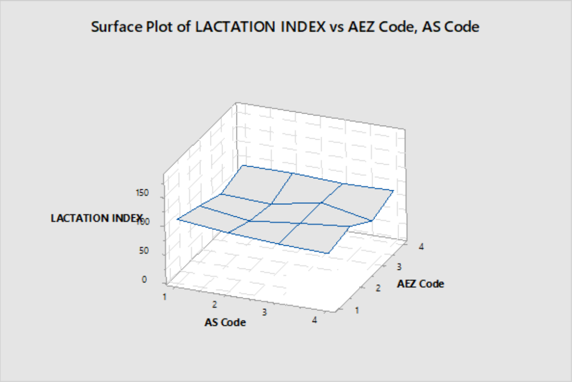


Figure 4. 8 Milk urea nitrogen response.

### 4.3.3.3 Dairy value traits' responses



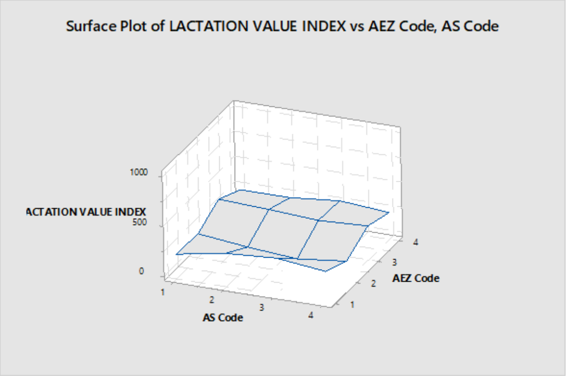
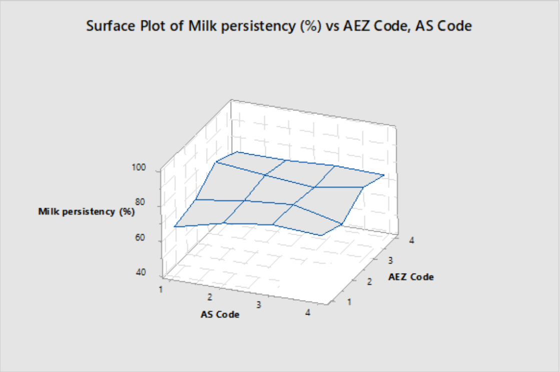


Figure 4. 9 Lactation index response.

Figure 4. 10 Lactation value index response.



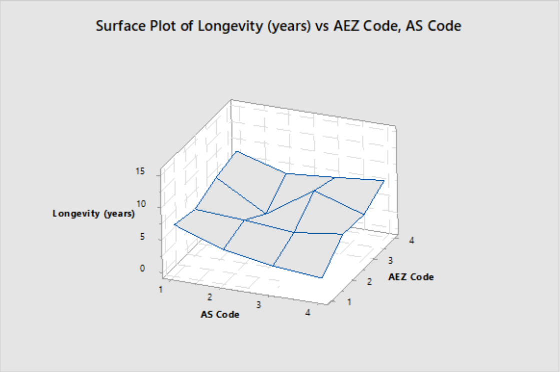


Figure 4. 11 Persistency response.

Figure 4. 12 Dam longevity response.

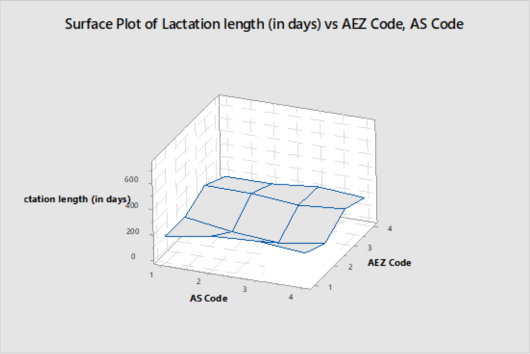


Figure 4. 13 Lactation length response.

## 4.4 Discussion

### 4.4.1 Assessment of Phenotypic plasticity index using different methods

#### 4.4.1.1 Variance and coefficient of variation-based method

Analysis of variance and coefficient of variation (CV) revealed significant phenotypic plasticity in somatic cell count (SCC), kid status score, litter size, and kidding ease score, indicating that environmental factors significantly influence these traits. The temperate zone exhibited the highest CV for SCC, suggesting increased environmental sensitivity, a finding consistent with research on German Holstein dairy cattle (Nada *et al.,* 2024). Similarly, the greatest plasticity in kid status score was observed in the temperate zone, while the arid, semi-arid, and semi-humid zones showed no variation. This pattern of environmental dependence contrasts with the findings of Grazer and Martin (2012), who reported that reproductive traits such as kid viability were highly influenced by climatic factors. Litter size displayed greater variation in the semi-humid and temperate zones, which supports studies in Murciano-Granadina goats indicating that litter size is highly responsive to environmental conditions (Mokhtari *et al.,* 2024). The kidding ease score, which also exhibited significant plasticity, followed a similar trend, with no variation in the arid, semi-arid and semi-humid zones, but increased sensitivity in the humid and temperate regions. These results are in agreement with observations in cattle, where kidding ease was more influenced by climate and nutrition in temperate zones compared to arid regions (Muzzo *et al.,* 2024).

In contrast, fat percentage, milk yield, lactose percentage, protein percentage, milk urea nitrogen, kidding interval, age at first kidding, birth difficulty score, lactation index, lactation value index, milk persistency, and dam longevity exhibited no significant phenotypic plasticity, suggesting that these traits are relatively stable across different agro-ecological zones. However, intra-zonal variations were observed, with milk persistence showing the highest CV in the temperate zone and dam longevity exhibiting greater variation in the arid zone. The stability of the traits of the milk composition is consistent with the findings of Saanen, Alpine and Nubian goats (A.S. Shuvarikov *et al.,* 2021), where the protein and fat content showed minimal environmental influence. Similarly, Gross (2022) reported that breeds intensively selected for milk production, such as Holsteins, tend to produce more milk than dualpurpose or beef breeds; however, long-term selection of strains within a breed under different environmental conditions can lead to divergent lactational performance. The limited plasticity observed in reproductive traits such as kidding interval and age at first kidding aligns with studies on crossbred dairy goats, indicating that these traits are strongly genetically controlled with limited environmental responsiveness (Desire *et al.,* 2017).

#### 4.4.1.2 Reaction norm-based method

Reaction norm analysis revealed significant phenotypic plasticity in several traits of Toggenburg goats, particularly reproductive performance and dairy value. In particular, lactose percentage, kidding ease score, and kid status score exhibited strong environmental influences, indicating a high degree of genotype-by-environment interaction. Similar results have been reported in Saanen goats, where the lactose content and reproductive traits demonstrated significant variation between climatic zones (Kljajevic *et al.,* 2018). Furthermore, lactation index, lactation value index, and milk persistency showed significant plasticity, suggesting that these traits respond to environmental variation, a trend also observed in Murciano-Granadina goats (Mokhtari *et al.,* 2024). Milk yield and milk urea nitrogen showed significant plasticity, which reinforces previous findings that milk production and composition traits in dairy goats are strongly affected by environmental conditions (Kljajevic *et al.,* 2018; Zhu *et al.,* 2020). The high $R^2$ value for milk production suggests that genetic expression for this trait is highly influenced by agro-ecological conditions, which aligns with the findings in Damascus goats, where milk production responded significantly to climate and feeding variations (YAKAN *et al.,* 2019). Birth difficulty score also exhibited significant plasticity, implying that environmental stressors play a role in kidding ease, a trend similar to that observed in Alpine goats (Sejian *et al.,* 2021).

On the contrary, fat percentage, protein percentage, somatic cell count, age at first kidding, kidding interval, and litter size did not exhibit significant phenotypic plasticity ($P > 0.05$), indicating that these traits remain relatively stable across different agro-ecological zones. These results align with previous studies on dairy breeds, where milk fat and protein content were found to be largely genetically determined with minimal environmental impact (National Research Council (US), 2016). Similarly, litter size and kidding interval have been reported as traits with strong genetic control, showing low responsiveness to environmental variation in dairy goat breeds (Chen *et al.,* 2025).

#### 4.4.1.3 Regression-based method

Regression-based model analysis revealed significant phenotypic plasticity in several traits of Toggenburg goats, highlighting the influence of environmental variation on genetic expression. SCC exhibited strong plasticity, suggesting that the genetic potential for SCC is highly dependent on agro-ecological zone (AEZ). This finding is consistent with previous studies on dairy cattle and goats (Dahl and McFadden, 2022; Desidera *et al.,* 2025), where SCC was found to vary significantly under different environmental conditions, probably due to heat stress and exposure to pathogens.re.ure. Similarly, dam longevity displayed a significant genotype-by-environment interaction, indicating that lifespan of dairy goats is influenced by environmental stressors, a trend also reported by Sejian *et al.* (2021).

Milk persistence showed significant plasticity, reinforcing its sensitivity to environmental variation. This supports previous findings (ALKaisy *et al.,* 2023), where persistency was found to be influenced by management practices, nutrition, and climate. Birth difficulty score also showed significant plasticity, implying that environmental conditions contribute to variation in kidding ease. Similar results have been observed in Damascus goats, where heat stress and nutritional deficiencies were associated with increased birth difficulties (Support, 2018).

In contrast, traits such as milk yield, fat content, lactose content, protein content, milk urea nitrogen, kidding ease score, kid status score, age at first kidding, kidding interval, litter size, lactation index, and lactation value index did not show significant genotype-by-environment interactions. This suggests that the genetic influence on these traits remains relatively stable across AEZs, which corroborates previous studies on dairy cattle (Mancin *et al.,* 2024). In particular, the lack of significant plasticity for milk composition traits contrasts with the findings in Saanen and Murciano-Granadina goats, where fat and protein percentages were found to be largely under genetic control with minimal environmental impact (Kljajevic *et al.,* 2018).

### 4.4.2 Surface plots of reproductive response of Toggenburg blood breed purity levels to variation across AEZs.

The findings show that kidding ease, kid status, and prolificacy of Toggenburg goats are significantly influenced by the interaction between genotype and environmental conditions, particularly in semi-arid and arid zones (AEZ 2 and AEZ 1). Difficult kidding was more prevalent in the F0 and Appendix A genotypes (AS Codes 1 and 2) in these regions, consistent with Robertson *et al.* (2020), who linked harsh environmental factors such as heat stress, poor quality food and water scarcity to increased risk of dystocia. Despite these challenges, the surface plot for kid status revealed limited phenotypic plasticity, indicating resilience among Toggenburg goats to produce healthy offspring in diverse environments. This is consistent with Ramachandran and Sejian (2022), who highlighted the reproductive adaptability of dairy goats in fluctuating climates. However, the surface plot for prolificacy showed some variation in litter size, with a slight decline in semi-arid and arid zones, particularly for genotype AS Code 4. This suggests a degree of phenotypic plasticity in response to environmental stress, as supported by Adjassin *et al.* (2022) and Mataveia *et al.* (2021), who reported reduced prolificacy under harsh weather conditions. The observed decrease in litter size may result from decreased reproductive efficiency due to stress-related impacts on ovulation rates and embryo survival, as noted by Sánchez-Dávila *et al.* (2015). Overall, while Toggenburg goats exhibit resilience in reproductive traits, environmental stressors can still influence their performance.

### 4.4.3 Surface plots of milk production responses of Toggenburg blood breed purity levels to variation across AEZs.

The surface plot for lactation milk production in Toggenburg goats exhibited a generally consistent trend, with only a slight decrease in milk production noted in the arid zone for StudBook Proper animals (AS Code 4), indicating low phenotypic plasticity for this trait across most agro-ecological zones (AEZs).). This finding is supported by previous research (Ahuya *et al.,* 2009; LRRD, 2014; Devendra and Haenlein, 2016), who highlighted the ability of dairy goat breeds, particularly Toggenburgs, to maintain stable milk production even under challenging environmental conditions. Additionally, better pasture quality and nutritional availability in temperate and sub-humid areas were associated with increased protein yield, corroborating Zhu *et al.* (2020). The study also revealed that genetically modified goat breeds tend to exhibit improved adaptation to fat yield, especially in temperate climates with optimal feed quality (Joy *et al.,* 2020). Furthermore, lower values of SCC values were observed in arid and semi-arid zones, likely due to harsher environmental conditions that reduce pathogen burdens, compared to higher SCC levels typically found in humid regions where udder health can be compromised (Bokharaeian *et al.,* 2023).). Lastly, elevated levels of MUN in sub-humid and temperate zones suggest that Toggenburg goats can effectively metabolise and excrete more urea nitrogen due to improved feed quality and access to nitrogen-rich forages, aligning with Goetsch (2019), who noted a correlation between higher levels of MUN land increased pasture quality and protein intake in temperate environments.

### 4.4.4 Surface plots of dairy value response of Toggenburg blood breed purity levels genotype to variation across AEZs.

The results of the current study are consistent with those of Mierliță (2023), who found that the lactation index of dairy goats remains relatively stable despite variations in feeding systems and pasture types, suggesting a genetic predisposition for reliable lactation performance. This observation aligns with Waineina *et al.* (2021), who demonstrated that matching goat genotypes to climate conditions, particularly in humid zones, improves lactation performance. Similarly, Timon and Baber (2024) emphasised the importance of genetic adaptation to local conditions for lactation success in West African breeds, especially under drought stress. Further supporting this trend, Gipson (2019) noted that genetic advances significantly improve milk persistence in dairy goats, particularly in humid and temperate climates. Additionally, Kaushik *et al.* (2023) highlighted that superior genetic goat breeds tend to have longer lifespans when raised in temperate and sub-humid environments, underscoring the positive impact of favourable habitats on livestock longevity. On the contrary, Sejian *et al.* (2021) pointed out the challenges faced by goats in arid zones, where environmental stressors such as heat and water scarcity can significantly reduce lifespans. Additionally, Miller and Lu (2019) demonstrated the influence of environmental factors on milk production, revealing that genetically modified dairy goats experience extended lactation periods under favourable climatic conditions. According to Lu and Miller (2019), goat breeds in temperate regions typically exhibit longer lactation cycles due to improved food availability and stable weather conditions.

## 4.5 Conclusion and Recommendations

### 4.5.1 Conclusion

In conclusion, there is phenotypic plasticity in reproductive traits, milk production traits, and dairy value traits of Toggenburg goat blood purity levels in different agro-ecological zones of South Africa. This study highlights the importance of considering genotype-environment interactions in breeding programs for Toggenburg goats. Among the methods assessed to evaluate phenotypic plasticity in dairy goats, the reaction norm-based method proved most effective, demonstrating significant interactions between GxE. While some traits, such as kid status and lactation milk production, exhibit relatively low phenotypic plasticity, others, such as kidding ease and milk protein production, are significantly influenced by environmental conditions. Signifying that a change in environmental conditions, i.e. decrease in temperature and increase in humidity (arid to temperate), indicated significant phenotypic plasticity of TOG blood purity levels on milk production/ reproductive/ dairy value traits. In this study, traits such as kidding ease and milk protein yield exhibited higher reactivity, with significant differences observed between AEZ and genotypes. Conversely, kid status and lactation milk yield demonstrated lower reactivity, indicating a more consistent performance regardless of environmental variations.

1. **Reproductivity**: Kid status was constant throughout environments, although prolificacy varied a little, especially in arid zones, and blood breed purity levels had a small impact. In general, Toggenburg goats consistently produced litters of consistent size in a variety of agro-ecological zones.
2. **Milk production traits**: The milk production of Toggenburg goats was not significantly affected by environmental influences in various agro-ecological zones, indicating a moderate degree of phenotypic plasticity in lactation production. The flatness of the surface plot indicated that, with the exception of arid regions, there is little impact of genetic background or environmental changes on milk production. The animals in Appendix A had lower protein yields, although they fluctuated very little in ideal environments such as temperate and sub-humid zones. On the contrary, the animals in Appendix B and StudBook Proper had a higher fat yield, suggesting a potential for increased performance, while the purity levels of F0 and StudBook Proper (AS Code 4) also had lower protein yields. Furthermore, goats in arid and semi-arid

regions had a lower SCC, indicating better udder health, while goats in more hospitable zones had a higher SCC, meaning that some breed purity levels are more susceptible to udder infections.

3. **Dairy value attributes**: The surface plot's flatness indicated that, across various agro-ecological zones, environmental factors have minimal impact on the lactation index. This implies that milk production in dairy goats can be enhanced by selecting the appropriate purity levels for a particular area. Compared to the foundation stock and Appendix A, StudBook Proper and Appendix B animals exhibited superior milk persistence. Furthermore, StudBook Proper and Appendix B animals live longer in healthier habitats, whereas Appendix A and foundation stock animals have shorter lifespans in harsher habitats, particularly in difficult environments, these two purity levels typically have longer lactation lengths than foundation stock and Appendix A animals, which have shorter cycles.

### 4.5.2 Recommendations

Farmers and breeders should develop separate breeding programs for different AEZs, focusing on selecting goats that are well adapted to the specific environmental conditions of each zone. In arid zones, prioritise traits related to tolerance to heat stress, efficiency of water use, and the ability to thrive on low quality forage.

They can also match genotypes to environments based on their performance characteristics. Appendix B and StudBook Proper genotypes appear to be better suited to more favourable environments, while the F0 and Appendix A genotypes may be more appropriate for less favourable environments.

Implementing management practices that mitigate the negative effects of environmental stressors, such as providing additional food during drought periods, ensuring access to clean water, and providing shade to reduce heat stress, would be of paramount importance.

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# CHAPTER 5

# GENERAL DISCUSSION, CONCLUSION, RECOMMANDATIONS, AND SCOPE FOR FURTHER RESEARCH

### 5.1 General discussion

This (mini)-dissertation examined the Toggenburg dairy goats' phenotypic plasticity with regard to milk production attributes in several South African agro-ecological zones. It investigated the interactions between animal and environmental factors that affect the yield using different methods to assess the phenotypic plasticity index. The results contribute to breeding and management strategies for sustainable production by offering important insights into the productivity and adaptation of dairy goats in various environments.

The findings showed that environmental factors including the kidding season and agro-ecological zones had a major impact on milk production. Although temperate zones supported the highest milk volume, semi-arid zones were linked to lower somatic cell counts and better milk fat production, indicating that these environments offer optimal conditions likely due to factors such as climate, forage quality, and thermal comfort that boost lactation performance. These results are consistent with research conducted by Das *et al.* (2016) and Toghdory *et al.* (2022), which highlighted the impact of environmental factors, including feed availability and climate, on the composition and yield of milk produced by dairy goats. According to research by Alhussien and Dang (2018), milk produced in spring also showed higher somatic cell counts, which may indicate more problems with udder health during this time of year. This suggests these areas may promote better udder health and milk quality, even if the overall milk volume is somewhat lower. Higher milk production was associated with mid-parities (2, 3, and 5 for male kids; 4 and 6 for female kids). Research by Lee and Kim (2006) found similar patterns linking mid-parity phases to peak lactation performance due to ideal physiological maturity. Additionally, parity ten was found to be essential to preserve milk persistence, strengthening the idea that, under suitable conditions, older goats may produce milk with greater resilience (Ithurbide *et al.,* 2022). This could also be used as selection approach aimed at enhancing long-term productivity and resilience in older does.

The results highlight significant environmental influences on traits such as somatic cell count (SCC), kid status score, kidding ease score, milk yield, and milk persistency, with reaction norm analysis identifying the strongest GxE interactions. Reproductive traits, including kid status score, litter size, and kidding ease score, exhibited high phenotypic plasticity, particularly in temperate and humid zones, this is because these traits are highly influenced by environmental factors. This has significant implications for breeding programs, suggesting that reproductive performance may vary across different environments and should be assessed with consideration of specific local conditions. Goats that exhibit strong reproductive success in one region may not show the same results in another, highlighting the critical role of genotype-by-environment interactions in trait evaluation. These results are consistent with the findings of Ben-moula *et al.* (2024) and Kraai *et al.* (2022), who reported that reproductive traits in goats are highly sensitive to climate variations. Similarly, milk production traits such as milk yield, lactose percentage, and milk persistency showed significant plasticity, in line with the study by Das *et al.* (2016), which emphasised the impact of environmental stressors such as temperature and humidity on dairy performance. In particular, SCC showed significant plasticity across agro-ecological zones, with the temperate zone showing the highest CV, points to increased susceptibility to udder health issues under certain climatic conditions. This emphasizes the importance of tailoring udder health management to local environments and potentially selecting animals that maintain more stable SCC levels across varying conditions. These results support the findings of Alhussien and Dang (2018), that SCC is a reliable indicator of environmental stress in dairy animals. On the contrary, traits such as fat percentage, protein percentage, age at first kidding, and kidding interval did not show significant plasticity in this study, possibly due to breed-specific differences compared to findings by Williams *et al.* (2021). Among the three methods assessed, the reaction norm approach emerged as the most effective for detecting phenotypic plasticity due to its ability to quantify both the magnitude and direction of GxE interactions. This aligns with Mulder (2016), who highlighted its superiority for breeding programs aimed at improving resilience to environmental variability. These findings underscore the importance of using robust methods like reaction norm models to inform breeding strategies for adaptive traits in livestock.

The analysis of phenotypic plasticity in Toggenburg goats using variance, coefficient of variation (CV), reaction norm, and regression-based methods highlights the significant influence of environmental factors on certain traits while revealing the stability of others. Traits such as somatic cell count (SCC), kid status score, litter size, and kidding ease score demonstrated substantial plasticity, particularly in temperate zones, where heightened environmental sensitivity was observed, this highlights the increased environmental sensitivity of these traits in more variable or intensive production systems. This implies that producers in temperate regions may encounter greater difficulties in maintaining consistent reproductive and health outcomes, and that animals raised there could benefit most from tailored management practices or environment-specific breeding strategies This aligns with findings in German Holstein cattle (Nada *et al.,* 2024) and Murciano-Granadina goats (Mokhtari *et al.,* 2024), which also exhibit environmental responsiveness in reproductive and health-related traits. Reaction norm analysis further emphasized GxE interactions for lactose percentage, milk persistency, and kidding ease, consistent with studies on Saanen goats (Kljajevic *et al.,* 2018) and Damascus goats (Yakan *et al.,* 2019). Conversely, fat percentage, protein percentage, age at first kidding, and kidding interval showed minimal plasticity, indicating strong genetic control with limited environmental responsiveness. This stability agrees with research on dairy breeds such as Saanen and Alpine goats (Shuvarikov *et al.,* 2021) and cross-bred dairy goats (Desire *et al.,* 2017). Regression-based analysis also highlighted significant plasticity in SCC and dam longevity due to environmental stressors, supporting findings in both dairy cattle and goats (Dahl and McFadden, 2022; Sejian *et al.,* 2021).

The majority of surface plots showed little to no phenotypic plasticity for milk production traits, indicating that the environment had little effect on milk production. The findings of Williams *et al.* (2021), who documented no variation in lactation performance across environmental gradients for specific dairy breeds, are consistent with this flat response throughout agro-ecological zones. However, some differences were noted between StudBook and Appendix B. The appropriate genotypes showed more flexibility and performed better in temperate and sub-humid climates. This is in line with research by Friggens et al. (2017) that emphasises how genetic robustness helps maximise performance in a variety of environments. Based on the GxE interaction appendix B (AS Code 3) and StudBook Proper (AS Code 4) animals showed superior lactation cycles, longevity, and milk persistency compared to foundation stock (F0) and Appendix A animals. This is because genetically advanced genotypes are better adapted to sustain performance across diverse environments, underscoring the importance of enhancing genetic selection programs while considering environmental compatibility and adaptability. These results are consistent with those of Products (1988), who found that GxE interactions were important factors in determining how well dairy goats lactated. Better feed consumption under favourable conditions is indicated by the elevated levels of milk urea nitrogen seen in temperate zones for Appendix B and StudBook Proper animals (Tshuma *et al.,* 2023).

The research noted traits like lactation milk yield and persistency showed consistency across agro-ecological zones, suggesting possible genetic regulation. However, these findings warrant caution due to reliance on secondary datasets, which may introduce biases from: Inconsistent data collection methods, limited environmental variation within zones, or small sample sizes for specific genotypes. These factors could mask true trait variability, making some traits appear not stable. Additionally, conflicting trends such as kid sex influencing milk yield differently across parities might reflect natural biological variation or unmeasured confounders such as parity structure, management practices, or uneven genotype distribution. One of the main drawbacks of this study is that molecular information, including genetic markers, which may have shed more light on the genetic foundation of the phenotypic flexibility and adaptability of Toggenburg goats was not included. The scope of the study was also limited to particular agro-ecological zones in South Africa, which would have limited the applicability of the results to other areas with distinct environmental conditions. Furthermore, in this study, differences in feed quality, nutritional management, and health interventions, all of which have a significant impact on milk yield and quality, were not taken into account.

## 5.2 General conclusion

This study examined the phenotypic plasticity of Toggenburg dairy goats, emphasizing on traits related to milk production in several South African agro-ecological zones. The results showed that although Toggenburg goats have a limited amount of phenotypic plasticity when it comes to producing milk, some genetic and environmental factors have a big impact on their adaptability and productivity. Agro-ecological zones and kidding seasons were important environmental considerations. Although temperate zones supported larger milk production but were more susceptible to udder infections, semi-arid zones promoted improved udder health and milk fat yield. This study highlights the importance of considering genotype-environment interactions in breeding programs for Toggenburg goats, thus a change in environmental condition i.e. decrease in temp and increase in humidity (arid to temperate) indicated significant phenotypic plasticity of TOG genotypes on milk production/ reproductive/ dairy value traits. Among the methods assessed for the evaluation of phenotypic plasticity in dairy goats, the reaction norm-based method proved to be the most effective. The importance of seasonal planning in breeding techniques was highlighted by healthier offspring born in winter. Appendix B and StudBook Proper genotypes showed higher milk persistency, longevity, and adaptation, especially in sub-humid and temperate zones, although genotype performance varied across agro-ecological zones. Although the foundation stock animals had shorter lifespans and lactation cycles, they were less adapted to harsher conditions and produced higher milk productions. Productivity was also affected by parity; Milk production peaked between parities 2 and 7, and parity 10 was essential to preserve milk persistence. These results emphasise how crucial it is to match management and breeding strategies with particular animal and environmental circumstances to maximise sustainability and productivity.

## 5.3 General recommendations

Winter kidding is linked to higher offspring health outcomes, farmers are encouraged to schedule their kidding during this season to increase kid health and survival rates. While temperate zones should be given priority for high milk production and improved udder health management to reduce the risk of infections, semi-arid zones should be used for milk production for the best fat production and udder health. Breeders and farmers should focus on StudBook Proper purity levels and Appendix B because of their adaptability and resilience in a variety of AEZs. Farmers can still use foundation stock animals, particularly if they are kept in controlled settings with adequate health care due to their increased milk production.

Farmers and breeders should develop separate breeding programs for different AEZs, focusing on selecting goats that are well adapted to the specific environmental conditions of each zone. In arid zones, prioritise traits related to tolerance to heat stress, efficiency of water use, and the ability to thrive on low quality forage. They can also match the purity levels of the breed to environments based on their performance characteristics. Appendix B and StudBook Proper purity levels appear to be better suited to more favourable environments, while F0 and Appendix A may be more appropriate for less favourable environments. Implementing management practices that mitigate the negative effects of environmental stressors, such as providing additional feed during drought periods, ensuring access to clean water, and providing shade to reduce heat stress, would be of paramount importance. The reaction norm-based method proved to be the most effective; thus, it is highly recommended as the method to use to evaluate the phenotypic plasticity of goats.

To maximise milk persistence, farmers and breeders are strongly advised to keep goats until parity 10, as this stage encourages a steady milk supply throughout time. Since mid-parities (2–7) exhibit the highest milk yield, it is recommended to carefully manage these stages to maximise peak production. Adapting methods according to the sex of the kid is also crucial; female kids increase milk production in parities 4 and 6, whereas male kids tend to drive higher milk production in parities 2, 3, and 5.

Udder health should be given top priority by farmers and breeders in temperate and sub-humid climates because these areas are linked to increased somatic cell counts, which can have an impact on milk quality. To reduce the risk of udder infections and guarantee consistent milk quality, regular medical checks and better cleaning techniques are crucial. Sustainable breeding practices must be a major priority in order to achieve long-term success. For breeding efforts to increase resistance, longevity, and productivity, genotypes must be aligned with certain agro-ecological zones. Farmers and breeders can greatly increase the sustainability and production of their Toggenburg dairy goat farming systems by implementing these specialised approaches.

## 5.4 Scope for further research

The future researcher should identify specific genes and physiological mechanisms that contribute to environmental adaptation in Toggenburg goats.

Future studies should focus on determining genetic markers related to traits related to milk production, reproductive success, and phenotypic plasticity. By making it possible to choose genotypes that are most appropriate for particular agro-ecological zones, this will aid in improving breeding methods. To verify the adaptability and robustness of Appendix B and StudBook Proper genotypes under various environmental circumstances, future research should also assess their long-term performance. More research is required to determine the effects of particular environmental factors, such as temperature, humidity, and soil quality, on milk composition and goat health, although this study found little phenotypic plasticity in milk yield across agro-ecological zones.

It is not yet clear how the nutrition and quality of the feed affect the health of the udder, the fat content and the milk production in different agro-ecological zones. Studies could investigate how Toggenburg goat performance is affected by locally accessible feed supplies and customised dietary supplements in various zones, particularly in dry and semi-arid areas. Under ideal circumstances, higher somatic cell counts (SCC) found in temperate and sub-humid regions suggest vulnerability to udder infection. Future research could examine the association between genotype-specific susceptibility, management strategies, and SCC. Lastly, studies could focus on the economic implications of implementing recommended practices, such as adopting Appendix B and StudBook Proper genotypes or modifying parity management.

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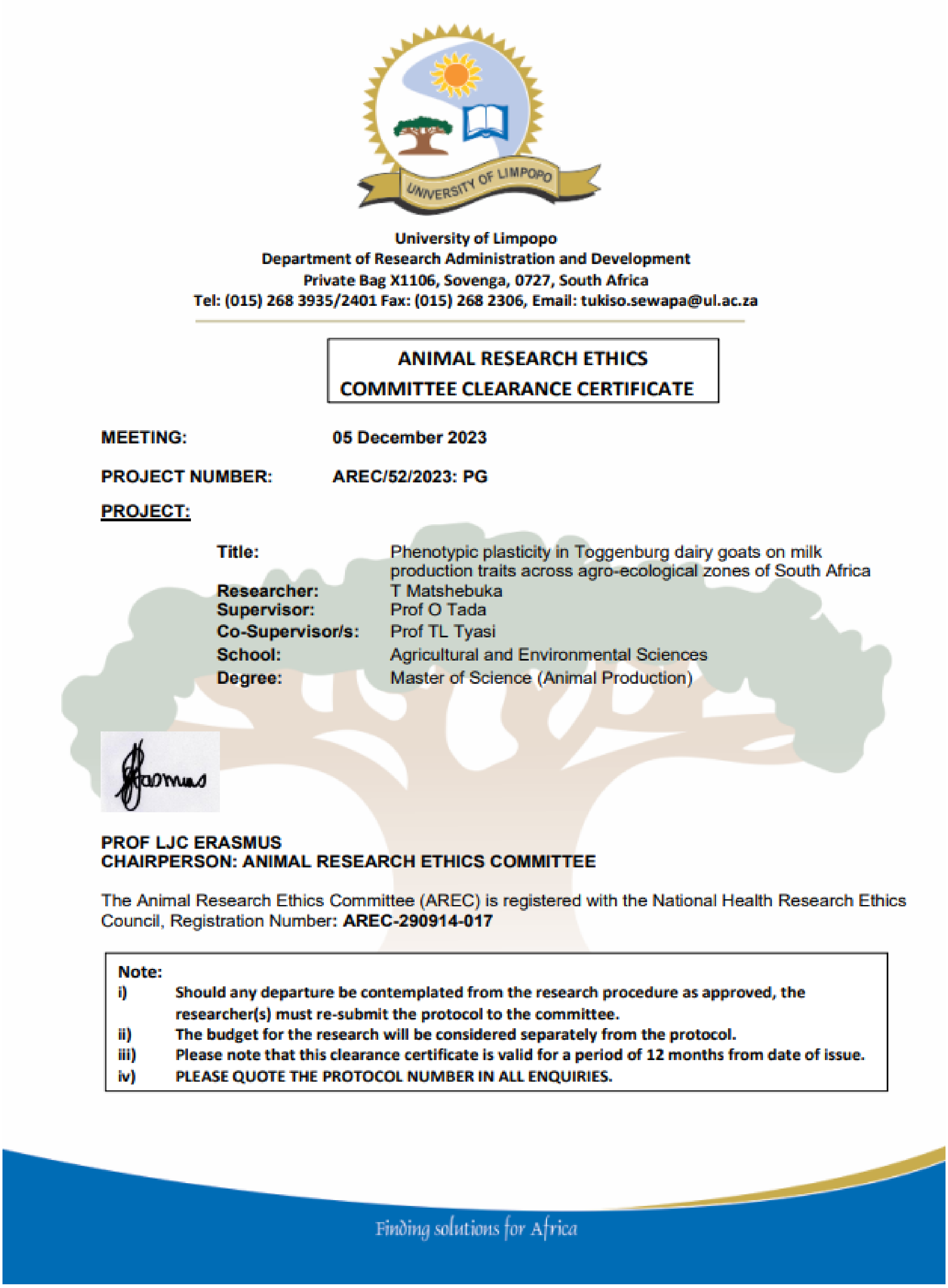
# CHAPTER 6

# APPENDICES

## Appendix A

## Animal research ethics committee clearance certificate



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**ANIMAL RESEARCH ETHICS COMMITTEE CLEARANCE CERTIFICATE**

**MEETING:** **05 December 2023**

**PROJECT NUMBER:** **AREC/52/2023: PG**

**PROJECT:**

| | |
|---|---|
| **Title:** | Phenotypic plasticity in Toggenburg dairy goats on milk production traits across agro-ecological zones of South Africa |
| **Researcher:** | T Matshebuka |
| **Supervisor:** | Prof O Tada |
| **Co-Supervisor/s:** | Prof TL Tyasi |
| **School:** | Agricultural and Environmental Sciences |
| **Degree:** | Master of Science (Animal Production) |

**PROF LJC ERASMUS**
**CHAIRPERSON: ANIMAL RESEARCH ETHICS COMMITTEE**

The Animal Research Ethics Committee (AREC) is registered with the National Health Research Ethics Council, Registration Number: **AREC-290914-017**

**Note:**
**i) Should any departure be contemplated from the research procedure as approved, the researcher(s) must re-submit the protocol to the committee.**
**ii) The budget for the research will be considered separately from the protocol.**
**iii) Please note that this clearance certificate is valid for a period of 12 months from date of issue.**
**iv) PLEASE QUOTE THE PROTOCOL NUMBER IN ALL ENQUIRIES.**

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Appendix B

Turnitin report

MATSHEBUKA MINI-DISSERTATION.docx

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