ASSAYING WATER REQUIREMENTS AND HYDRIC STRESS TOLERANCE OF THE SOUTH AFRICAN INDIGENOUS SHEEP GENETIC RESOURCES FOR WATER AND FOOD SECURITY

Report to the
Water Research Commission

by

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EXECUTIVE SUMMARY

Sheep production is a major socio-economic activity in South Africa owing to the arid nature of the country's landscape. The national flock size currently stands at about 22 million, with over half farmed in the arid and semi-arid areas of South Africa. Water scarcity, however, poses a serious challenge to sheep meat production in these dryland farming areas. There is scant documentation regarding the water-saving strategies that can be used during water scarcity periods. Such information is important given that South Africa is presently ranked the 30th driest country in the world. The current study, therefore, reviewed potential local recovery and resilience strategies for adoption in dry areas, evaluated the determinants of smallholder farmers' perceived effects of water scarcity on sheep production in the dry ecozones of the Cape Provinces in South Africa and identified local response strategies. This was followed by two comparative studies evaluating the water requirements, hydric stress, production performance, and meat quality attributes of the common South African sheep breeds under an intensive (i.e. feedlot) system.

The primary local recovery strategies identified in literature include the use of adapted breeds, water restriction and deprivation techniques, sustainable rangeland management practices, succulent feeds, and water stress alleviators. Investments in water supply enhancement and conservation infrastructure and technologies, decision support tools, capacity building, research, laws, policies, and incentives that optimise water use efficiency along the sheep meat production value chain were among the recommended key water resilience strategies. A survey with 252 participants was conducted to investigate the contextual factors that influence smallholder farmers' perceptions of the effects of water scarcity on sheep production in the Cape Provinces of South Africa and identify their local response strategies. Sheep producers living in semi-arid ecozones, extensive farmers, women, less educated farmers, owners of non-tropically adapted breeds, and farmers entirely relying on livestock income were more likely to perceive water scarcity as having a negative effect on drinking water quality, sheep production, and marketing. Several strategies have been used by smallholder farmers to respond to water scarcity, including switching between water sources, offering supplementary water, feed, and shade, and using breeds that are adapted to the dry environments.

The third objective evaluated the nutrient digestibility, water requirements, production performance, and meat quality attributes of one exotic (Merino), two indigenous (Pedi and Damara), and three composite (Dohne Merino, Dorper, and Meatmaster) South African sheep breeds during a 42-day trial. As expected, Pedi, because of its smaller body size, had the lowest feed intake. Interestingly, the Damara had a comparable water balance to the three composite breeds, despite it and the Meatmaster having superior nutrient intake, dry matter digestibility, and nitrogen balance. A similar trend was observed with average daily gain, which was greater for the Damara and Meatmaster than the other breeds. The economic analysis, expressed as income over feed costs, was in the order of Dohne Merino > Meatmaster > Merino > Dorper > Damara > Pedi. The two indigenous sheep breeds had the lowest

intramuscular fat content, with the Pedi having a more desirable fatty acid profile compared to the other breeds. Minor and inconsistent breed effects were reported for meat shelf-life and sensory attributes. However, the Merinos had slightly higher meat tenderness and juiciness than other breeds.

The final study, also conducted over 42 days, compared the effects of water restriction (0, 10, and 20%) and breed on the production performance and meat quality attributes of two indigenous (Pedi and Damara) and two composite (Dohne Merino and Meatmaster) sheep breeds. No water restriction × breed interactive effects were observed for meat production and quality parameters. However, as the level of water restriction increased, there was a slight reduction in the final live weight and increase in meat redness. Meatmaster and Pedi had a lower daily water intake than Dohne Merino. However, Meatmaster and Dohne Merino had superior carcass weights, income-over-feed costs, low carcass pH, and more tender meat than the other breeds. In general, daily water restrictions up to 20% did not adversely influence growth, carcass and meat quality attributes the common South African sheep breeds.

Overall, both animal trials showed that though the Pedi breed had the highest feed and water efficiencies, it had lighter and leaner carcasses than other breeds. Meatmaster had superior water utilisation efficiency comparable to Pedi but had superior meat production and quality attributes comparable to the Merinos. Water restriction of up to 20% neither had negative effects on meat production nor quality attributes. It was concluded that feedlotting the Meatmaster breed and subjecting lambs to water restriction up to 20% in the feedlot are potential water-saving strategies for South African sheep farmers. Given that water scarcity in South Africa is predicted to worsen, these water-saving strategies should target farmers with low drought adaptive capacity, particularly less educated women entirely relying on livestock income and farming extensively with non-adapted breeds in the semi-arid ecozones of South Africa.

Current study created new knowledge and information on farmers' perceptions on water scarcity and their contextual influencing factors, and water scarcity response strategies. New knowledge about water, feed and meat production efficiencies and water stress tolerance of local sheep breeds was generated. However, additional research to assess other indigenous and composite breeds and higher levels of water restriction, which will enable the determination of the threshold levels beyond which either meat production or quality is compromised is critical. Findings of such studies should allow enable producers, especially those with low drought adaptive capacity to save water without adversely compromising sheep meat production and quality.

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ii. Mupfiga, S., Katiyatiya, C.L.F., Chikwanha, O.C., Molotsi, A.H., Dzama, K. and Mapiye, C., 2022. Meat production, feed and water efficiencies of selected South African sheep breeds. Small Ruminant Research, 214, 106746. https://doi.org/10.1016/j.smallrumres.2022.106746. (Impact factor: 1.611). *The paper is part of chapter 4.*

iii. Halimani, T., Marandure, T., Chikwanha, O.C., Molotsi, A.H., Abiodun, B.J., Dzama, K. and Mapiye, C. 2021. Smallholder sheep farmers' perceived impact of water scarcity in the dry ecozones of South Africa: Determinants and response strategies. Climate Risk Management, 34, 100369. https://doi.org/10.1016/j.crm.2021.100369. (Impact Factor: 4.090). *The paper is part of chapter 3.*

iv. Chikwanha, O.C., Mupfiga, S., Olagbegi, B.S., Katiyatiya, C.L.F., Molotsi, A.H., Abiodun, B.J., Dzama, K. and Mapiye, C., 2021. Impact of water scarcity on dryland sheep meat production and quality: Key recovery and resilience strategies. Journal of Arid Environments, 190, 104511. https://doi.org/10.1016/j.jaridenv.2021.104511. (Impact Factor: 2.759). *The paper is part of chapter 2.*

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i. Chikwanha, O.C., Mupfiga, S., Olagbegi, B.R., Katiyatiya, C.L.F., Molotsi, A.H., Abiodun, B.J., Dzama, K. & Mapiye, C. 2021. Water management strategies for reducing water stress on dryland sheep meat production and quality. (Oral). 52^{nd} virtual Congress of the South African Society of Animal Sciences, 10-12 August 2021. *The proceeding is part of chapter 2.*

LIST OF ABBREVIATIONS

µm	Micromolar
a*	Meat redness
AA	Arachidonic acid
ADFom	Acid detergent fibre, exclusive of ash
ADG	Average daily gain
AgriSA	Agri South Africa
ALA	Alpha-linolenic acid
AMSA	American Meat Science Association
aNDFom	Neutral detergent fibre, exclusive of ash
AOAC	Association of Official Agricultural Chemists
b*	Meat yellowness
CL	Cooking loss
CLA	Conjugated linoleic acid
COVID-19	Coronavirus Disease 2019
CP	Crude protein
DAFF	Department: Agriculture, Forestry and Fisheries
DHA	Docosapentaenoic acid
DM	Dry matter
DMI	Dry matter intake
DPA	Docosapentaenoic acid
DSA	Descriptive Sensory Analyses
DWI	Daily water intake
EE	Ether extract
EPA	Eicosapentaenoic acid
FA	Fatty acids
FAME	fatty acid methyl esters
FAO	Food and Agriculture Organization
FAOSTAT	Food and Agriculture Organization Corporate Statistical Database
FCR	Feed conversion ratio
FESCAGRI	Stellenbosch University Research Ethics Committee: Social Behavioural and Education Research committee
FRAP	ferric reducing ability power
$g\ d^{-1}$	Grams per day
$g\ N\ d^{-1}$	Grams of nitrogen per day
GIS	Geographic information system
GPS	Global position system
ha	Hectare
ICT	Information Communication Technology
IMF	Intramuscular fat
iNDF	Indigestible neutral detergent fibre
IOFC	income-over-feed cost
IPCC	Intergovernmental Panel on Climate Change
ivNDFd	In vitro neutral detergent fibre digestibility
kg	Kilogram
L	Litre
L*	Meat lightness

LA	Linoleic acid
Lignin (sa)	Lignin: determined by solubilisation of cellulose with 72% sulphuric acid.
LL	longissimus lumborum
LSMEANS	Least square means
LT	longissimus thoracis
LTL	longissimus thoracis et lumborum
LW	Live weight
$LW^{0.75}$	Metabolic body weight
MDA	Malondialdehyde
mg dL^{-1}	Milligram per decilitre
mM	Millimolar
MUFA	Monounsaturated fatty acids
N	Nitrogen
n-3	Omega-3 fatty acids
n-6	Omega-6 fatty acids
NaCl L-1	Sodium chloride per litre
NFC	Non-fibrous carbohydrates
nm	Nanomoles
OECD/ FAO	Organisation for Economic Co-operation and Development/ Food and Agricultural Organization
OM	Organic matter
pH_{24}	pH at 24 hours
ppm	Parts per million
PUFA	Polyunsaturated fatty acids
RA	Rumenic acid
REC: ACU	Research Ethics Committee: Animal Care and Use
RH	Relative humidity
RI	retention indices
SAMIC	South African Meat Industry Company
SANS	South African National Standards
SAS	Statistical Analysis System
SD	Standard deviation
SFA	Saturated fatty acids
SU-HREC	Stellenbosch University Humanities Research Ethics Committee
TBARS	Thiobarbituric acid reactive substances
Tdb	Dry bulb temperature
TFC	Total feed costs
THI	Temperature-Humidity Index
TI	Total income
TNZ	Thermoneutral zone
VA	Vaccenic acid
WBSF	Warner-Bratzler shear force
μM	Micromolar

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CHAPTER 1 - INTRODUCTION

1.1 Motivation

Sheep are an important food and fibre source in many countries, including South Africa (Chikwanha et al., 2018). More than 25% of the global ruminant population is sheep (Marino et al. 2016), and their meat is one of the world's four major meat categories along with beef, pork, and chicken. In 2014, the global production of sheep meat amounted to 8.7 million metric tons, and the value of trade was more than US$6.7 billion (AHDB, 2015). In South Africa, sheep farming (with a total flock size of about 22 million) is one of the largest livestock sectors and makes a valuable contribution to household, provincial, and national economies (Chikwanha et al., 2018). This is especially true in smallholder areas where the people are poor and sheep farming is considered a major source of food, ready cash-income, and social security. In South Africa, drought is one of the major threats to the national flock (Bauer and Scholz, 2015). In 2015 for example, it reduced the sheep breeding stock and resulted in a shortage of sheep products for the following two years (Molotsi, 2017). In 2016, the trade balance for fresh and frozen mutton was reduced (-$15.9 million), and approximately 8 766 tonnes of meat ($19.4 million) were imported (Lombard and Rooyen, 2017). To counteract the threat of drought on lamb meat production, it is critical to investigate various scenarios of sheep farming in South Africa under water stress conditions and develop appropriate adaptation and mitigation strategies.

Although lamb meat production is affected by various climatic factors, drought seems to be the major factor. Hydric stress combined with nutritional and heat stress are considered major factors negatively affecting the physiological homeostasis of sheep, consequently compromising their health status, welfare, productive, and reproductive performance (Jaber et al., 2013; Chedid et al., 2014; Sejian et al., 2014). Furthermore, hydric stress reduces meat yield and adversely affects meat quality by making it drier and darker in colour (Rana et al. 2014). However, the ability of sheep to survive, reproduce, and maintain homeostasis during drought conditions depends on their genetic diversity (Molotsi, 2017). But, at present, there is little if any information regarding the water requirements and stress tolerance of many South African sheep breeds that can be used during water scarcity periods.

Several studies have projected an increase in water scarcity in the future. For example, lack of freshwater resources was listed as the largest global risk in terms of its potential impact over the next decade (World Economic Forum, 2015). However, smallholder farmers in low-income countries, particularly those in the arid and semi-arid areas, are most vulnerable to water scarcity due to a lack of drought adaptation and/or mitigation capacity, as well as a lack of good governance and resources to invest in water infrastructure (IPCC, 2014). Various areas in South Africa, especially the Cape Provinces (Western Cape, Northern Cape, and Eastern Cape), have been experiencing a series of severe droughts in the past few years (Araujo et al., 2016) and were recently declared provincial disasters. Meanwhile, there are indications that, due to projected reduced precipitation, surface and groundwater supplies, increased temperature, climate change, and human population (Benhin, 2008; Engelbrecht, et al., 2015; Diasso and Abiodun, 2017), the impacts of the future drought over these provinces might be more severe than in the past. So, the fast-changing climate could affect sustainable production lamb meat through reduced water and feed intake, variation in energy and protein metabolism, and alterations in water and mineral balances (Finocchiaro et al., 2005; Marai et al., 2007). Therefore, with the projected increases in drought in South Africa, long-term water management strategies should focus on increasing the utilisation efficiency of drinking water for sheep to ensure sustainable food, nutrition, income, and social security.

Several water stress management strategies are available, but their availability to farmers depends on their access to water and energy, the price they are willing to pay, and the farming system they have adopted (Jaber et al., 2013). For South Africa, promising low-cost water scarcity management strategies for smallholder sheep farmers include the use of breeds that have low water requirements and/or high hydric stress tolerance (Mdletshe et al., 2018). However, to understand the complexity of water scarcity impacts at the local and provincial scale, it is important to first consider farmer perceptions of drought impacts, their local adaptation measures, and administrative mitigation strategies. This will help to understand the challenges that farmers face so that appropriate water scarcity mitigation and adaptation strategies that directly address the circumstances that farmers are exposed to can be devised.

1.2 Contextualisation

South Africa is facing one of the worst droughts to hit the southern African region in 30 years. The drought is threatening lamb meat production mainly because of its impact on fodder and water availability. The Western Cape Province (WCP), for example, has so far been forced to slaughter more than 20% of its total sheep population (2.8 million) due to the 2017-18 drought. This adversely affects the sustainability of lamb meat production, and threatens household, provincial, and national food, nutrition, and income security. The frequency and intensity of drought in South Africa are expected to continue increasing in the coming years because of the changing climate. As a result, the country will increasingly face growing pressure on the sustainable use of its freshwater resources, especially in arid and semi-arid regions. Among foods, animal products are the highest consumers of water. The reduction in the pressure on freshwater resources from animal food products is one of the major challenges for South Africa. In this regard, farmers' perceptions of drought impacts are important to inform decision makers on its causes, impacts, various adaptation responses, and possible mitigation measures perceived at the local level to sustainably improve food, nutrition, and income security. The data will help local, provincial, and national governments develop comprehensive water management and efficient utilisation plans for improved lamb meat production in drought-stricken areas.

The indigenous breeds of sheep in South Africa, such as the Damara (Almeida, 2011) and Namaqua Afrikaner (Cloete et al., 2013), outperform exotic breeds for fitness traits such as survival and tick resistance (Molotsi, 2017). For example, Damara is superior to the South African Mutton Merino (SAMM) in its ability to maintain plasma changes during dehydration by excreting more concentrated urine (Stockman, 2006). The indigenous Nguni sheep breeds have been shown to have a higher genetic diversity in adaptive traits than the Merinos (Hlophe, 2011). A study by Schoeman and Visser (1995) demonstrated that Blackhead Persian had lower water requirements than Dorper and SAMM. Burger (2015) reported that Namaqua Afrikaner meat quality was comparable to Dorper and SAMM. Little is, however, known about the water requirements, hydric stress tolerance, and the effects of hydric stress on meat production and quality of sheep breeds indigenous to South Africa. Information about sheep water requirements and hydric-stress tolerance is essential for managing their production, health, and welfare. The use of sheep breeds that drink less water and/or tolerate hydric stress could be the way forward for managing South Africa's growing water scarcity trends. This may break the nexus between poverty and vulnerability to water scarcity for smallholder sheep farmers and build the capability to manage current and future water scarcity induced shocks at the household and national levels.

1.3 Aims

The project successfully achieved the following aims:

1) Investigation of sheep farmers' perceptions of drought impact, local adaptation measures, and administrative mitigation strategies in the Cape Provinces of South Africa;
2) Assessment of water requirements, meat production and quality of sheep breeds commonly raised in South Africa and;
3) Determination of the impact of hydric stress on meat production and quality of sheep breeds commonly raised in South Africa.

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CHAPTER 2 - IMPACT OF WATER SCARCITY ON DRYLAND SHEEP MEAT PRODUCTION AND QUALITY: KEY RECOVERY AND RESILIENCE STRATEGIES

The work was published in Journal of Arid Environments, 190, 104511

2.1 Summary

Water scarcity is among key the challenges facing sheep production in the arid and semi-arid areas and is predicted to worsen in future. Despite sheep in dry areas being capable of surviving relatively long periods with little water, deficiency of this essential nutrient produces lightweight carcasses and dark, dry and less tender meat. Responses to impacts of water scarcity have often been reactive rather than proactive, focusing on crisis rather than risk management. To effectively minimise the impact of water scarcity on dryland sheep meat production and quality, water-scarce countries should adopt a new paradigm for water management aimed at risk reduction. This entails identification and adoption of a menu of local recovery and resilience interventions spanning the spectrum from management of water, feed and animals to stakeholder capacitation. Most of the existing recovery and resilience strategies in water-scarce sheep producing countries have, however, not been widely adopted due to lack of evidence, resources, and adaptive capacity. The current review, therefore, discusses the impacts of water scarcity on sheep meat production and quality, and identifies a portfolio of local recovery and resilience strategies for adoption by dryland countries.

Keywords: Drylands, Meat quality, Resilience, Resource-limited farmers, Sheep production, Water scarcity.

2.2 Introduction

Sheep production is widespread in arid and semi-arid (i.e. dry) regions, with Asia and Africa comprising 42.6% and 31.7% of the 1.2 billion global sheep population, respectively (FAOSTAT, 2020). In these regions, sheep production is mainly challenged by water scarcity (Ibidhi and Ben Salem, 2019), which is further exacerbated by high population growth rates, climate change and variability, lack of preparedness and limited response capacity to natural hazards (Opiyo et al., 2015). Water scarcity can be broadly defined as either insufficient supply of water (i.e. quantity), or lack of access to clean, safe water to meet water use demand (Food and Agriculture Organisation, 2012). In the context of this review, water scarcity refers to insufficient supply of clean, safe water to meet water use demand for sheep production.

Sheep in the dry environments are mostly owned by resource-limited producers and have comparative advantages over large ruminants including short gestation period, high prolificacy and small size (Devendra, 2001). More importantly, they are less land, labour and capital intensive and often thrive under harsh environments (Akinmoladun et al., 2019). During prolonged hot-dry seasons, grazing sheep under extensive production systems often go for days without drinking water as most water sources are usually dry, have limited available water of poor quality or far from rangelands (Alamer and Al-Hozab, 2004; Castro et al., 2017). To this end, sheep in dry areas have infrequent access to water, often consume water of poor quality as well as feed with low moisture content and nutritional value (Akinmoladun et al., 2019; Alamer and Al-Hozab, 2004). Inadequate water intake, low fodder supplies and heat stress are considered to be the major factors negatively affecting physiological homeostasis of sheep, consequently compromising their immunity, growth and reproductive performance (Chedid et al., 2014). In addition, these factors may reduce meat yield and adversely affect meat quality by making it drier, less tender and darker in colour (Gregory, 2010; Jacob et al., 2006). This consequently results in huge economic losses, especially for resource-limited producers whose livelihood are supported by engaging in sheep marketing.

The demand for high biological value animal foods is expected to double by 2050 (Akinmoladun et al., 2019). The increased production to keep pace with the projected demand for animal products is expected to strain the existing freshwater resources (Food and Agriculture Organisation, 2012). To effectively respond to the impacts of water scarcity on sheep meat production and quality, a set of integrated sustainable response strategies ranging from management of water, feed and animals to stakeholder capacitation are required. The objective of this review is, therefore, to discuss the impacts of water scarcity on sheep meat production and quality; and identify key recovery and resilience response strategies for adoption in dry areas.

2.3 Global sheep meat production and contribution to sustainable livelihoods

In 2018, the top five sheep producing countries in the world were China, Australia, India, Nigeria and Sudan, which accounted for 32% of the global share (FAOSTAT, 2020). On average, global sheep meat production totalled 9.0 million tons per annum for the period 2009 to 2018, with Asia and Africa contributing 51.2% and 20.1%, respectively (FAOSTAT, 2020). According to the OECD/ FAO (2018) Agricultural Outlook, the period 2018 to 2027 is expected to experience a greater rate of sheep meat production relative to the previous decade, with greater demand from developing countries.

Sheep in developing countries serve as a key source of economic sustenance for weaker segments of the society as who reside in arid and semi-arid areas (Akinmoladun et al., 2019). They are a major sustainable livelihood option for resource-limited producers, and their rearing is often embedded in people’s culture. In smallholder farming systems, sheep offer a multi-facet utility for meat, wool, skins, leather, manure, flexible financial reserve and several socio-cultural uses (Akinmoladun et al., 2019; Devendra, 2001). This is contrary to large-scale producers who mainly target wool and meat. Phenotypically, sheep can be grouped into two classes; fat-tailed and thin-tailed (Mohapatra and Shinde, 2018). Globally, fat-tailed sheep account for 25% of the population and contribute nearly twice as much meat as thin-tailed sheep (Mohapatra and Shinde, 2018).

2.4 Sheep water requirements

Water is an essential nutrient in sheep production systems and is required for all metabolic processes necessary for life. As body water is lost through evaporation, respiration, defecation and urination, it is replenished either from drinking, feeding or metabolic processes (Araújo et al., 2010). Generally, water in feeds may range from a low of 5% in dry grains to about 90% in young, fast-growing grasses (National Research Council, 1981). Metabolic water can contribute up to 5-15% of total water requirements (Chedid et al., 2014). However, drinking water is the main source required to satisfy animals' water requirements, and is largely obtained from either surface (i.e. rivers, streams, dams and lakes) or ground (i.e. boreholes, wells and springs) sources (Peden et al., 2007). Drinking water intake for sheep vary from 5 to 25% of body weight, and is largely influenced by several factors including water quality and temperature, type and amount of feed, feed intake, farming system, individual animal, age, breed, sex, animal physiological state, air temperature and humidity (Akinmoladun et al., 2019; Araújo et al., 2010; Ibidhi and Ben Salem, 2019). For sound water management and future planning, it is important to understand the impact of water scarcity on meat production and quality.

2.5 Effects of water scarcity on sheep production and meat quality

The effects of reduced water intake on meat production and quality can either be positive or negative depending on duration and severity of water inadequacy (Chedid et al., 2014; dos Santos et al., 2019; Silanikove, 1992). Overall, inadequate water intake results in a wide range of physiological responses, which adversely affect animal health, reproductive efficiency, growth performance and product quality, and sometimes result in death (Chedid et al., 2014; dos Santos et al., 2019; Jaber et al., 2013). In the main, small ruminants are more tolerant to reduced water intake and poor water quality as they employ various physiological, morphological and behavioural response mechanisms (Chedid et al., 2014).

Overall, water intake is positively correlated with dry matter intake (DMI) (Jaber et al., 2013; Silanikove, 1992). This is associated with postprandial hyperosmolality reduction of the ruminal fluid (Chedid et al., 2014; Jaber et al., 2013; Silanikove, 1992). Generally, feed intake in ruminants causes secretion of huge quantities of saliva and gastric juices, which often decreases blood plasma and increase osmolality (Chedid et al., 2014; Jaber et al., 2013; Silanikove, 1992). This triggers an upsurge in the animal's propensity to drink water while feeding (Chedid et al., 2014). Several studies have reported marked reductions in sheep feed intake after exposure to prolonged periods of dehydration (Al-Ramamneh et al., 2012; Alamer and Al-Hozab, 2004; dos Santos et al., 2019). Animals under water stress tend to economise body water by reducing feed intake, and consequently heat dissipation (Alamer and Al-Hozab, 2004; Silanikove, 1992).

Rahardja et al. (2011) observed that outdoor raised sheep (18-39°C) restricted up to 50% *ad libitum* water intake had 11.8% reduction in organic matter (OM) intake compared to the indoor group (18-30°C). This mimics conditions prevailing under extensive production systems in arid and semi-arid regions, where triple challenges of water, heat and nutritional stress are prevalent (Chedid et al., 2014;

Silanikove, 1992). However, reduced feed intake is often accompanied by decreased rumination, saliva secretion, motility and passage rates in the rumen (Silanikove, 1992). Digesta is, therefore, retained longer within the rumen, allowing rumen microbes more time to break down structural carbohydrates, hence, increase nutrient digestibility (Silanikove, 1992). Water intake in general is positively correlated with nutrient intake (Jaber et al., 2013), with temperate breeds experiencing greater reduction in feed intake compared to tropical breeds in arid and semi-arid areas (Silanikove, 1992).

Decline in feed intake because of low water intake by animals partially explains the observed decreases in body weights (Table 2.1) and carcass weights, as these variables are natural markers of nutrient intakes and directly reflect on animal performance (dos Santos et al., 2019; Silanikove, 1992). Overall, water-restricted sheep lost between 1.1 and 9.6% of body weight, whilst water-deprived sheep lost between 1.2 and 21.5% of body weight (Table 2.1). Even though feed and water intake reductions affect body weight, immediate loss in weight could be largely attributed to body water losses (Alamer and Al-Hozab, 2004; Degen and Kam, 1992; Silanikove, 1992).

Studies evaluating the effects of water intake on sheep carcass and meat quality attributes have not produced consistent findings (dos Santos et al., 2019; Jacob et al., 2006). Neither Dos Santos et al. (2019) nor Jacob et al. (2006) reported any effects of low water intake on carcass weights of lambs. (Jacob et al., 2006), however, reported that the *semitendinosus* muscle had lower dry matter compared to the *semimembranosus* and the *longissimus thoracis et lumborum* after withholding access to water for 48 h preslaughter. This was attributed to differences in muscle fibre types, with *semitendinosus* having lower type I and IIA muscles, which had smaller cross-sectional area, corresponding to less water (Jacob et al., 2006). Jacob et al. (2006) noted that dehydration of lambs may result in meat that has high ultimate pH, and consequently darker in colour, with low drip and cooking losses. Meat tenderness was affected by deprivation period with lambs deprived water of 3 days having less tender meat compared to those deprived for either 1 or 2 days (dos Santos et al., 2019). Generally, chronically stressed animals have reduced glycolytic activity, high ultimate pH (5.8-6.2) and decreased proteolytic activity post-mortem, resulting in dark-coloured and less tender meat (Gregory, 2010; Miranda-de la Lama et al., 2009). Research on effects of reduced water intake on meat quality is important to validate these findings. Reduced water intake increased proportions of vaccenic acid (VA) and eicosapentaenoic acid (EPA), while that of rumenic acid (RA) and docosapentaenoic acid (DHA) decreased (dos Santos et al., 2019). These findings suggest that reduced water may influence microbes responsible for biohydrogenation and/ or *de novo* synthesis of fatty acids. Hence, further research is important given that EPA, DHA, RA and VA seem to promote human health and wellbeing (Chikwanha et al., 2018).

With regards to water quality, most studies have focused on salinity, but the term also encompasses taste, colour, turbidity, microorganisms, minerals, organic compounds, and other natural or chemical contaminants (Castro et al., 2017; De Moura et al., 2016; Yousfi et al., 2016). Yousfi et al. (2016)

reported an increase in water intake of Barbarine lambs, with those having access to salt-enriched water (i.e. 7 g sodium chloride [NaCl L^{-1}]) drinking more water than control lambs (i.e. 4.6 vs 2.48 litres d^{-1}). The higher intake of saline water by sheep could be linked to their possible mechanism of maintaining the salt-water balance by reducing the salt levels in the blood. Apart from the increased intake of saline water, Yousfi et al. (2016) did not observe any changes in feed intake, nutrient digestibility and utilisation. However, this merits further research as the ion imbalance caused by consuming saline water might also affect the preceding parameters.

Generally, saline levels of less than 10000 ppm have neutral effects on sheep body weight, carcass traits and meat quality (Castro et al., 2017; De Moura et al., 2016; Yousfi et al., 2016). In contrast, Assad and El-Sherif (2002) observed an 8.4% decline in body weight for ewes drinking saline water containing 13 535 ppm total dissolved solids. This could be attributed to hyperfunctioning of the liver because of high salt concentration coupled with decline in plasma glucose as sheep tend to expend more energy to cope with the saline load, which exerts stress on the liver (Assad and El-Sherif, 2002). Although there are no recommended salinity levels for sheep, some breeds tolerate salinity levels of up to 10000 ppm without compromising meat production and quality. This is important given that the water salinity challenge in arid and semi-arid regions is escalating (Assad and El-Sherif, 2002; Yousfi et al., 2016), which could in future compel farmers to offer saline water to sheep. Whilst knowledge on the effects of water quantity and quality on meat production and quality is being developed, managing livestock to reduce negative impacts of water scarcity remains a challenge. It is therefore imperative to develop sustainable water scarcity recovery and resilience strategies that promote climate-smart sheep production in dry regions.

2.6 Water scarcity recovery and resilience strategies for dryland sheep production

Despite the variability and complexity of weather and climate patterns, dryland sheep farmers have always employed their accumulated environmental indigenous knowledge and adaptation mechanisms to cope with water scarcity (Opiyo et al., 2015). This intimate relationship has enabled famers to protect and continuously exploit their changing surroundings, thereby empowering them to sustain animal productivity and livelihoods even under challenging times (Opiyo et al., 2015; Sejian et al., 2015). To sustain sheep production under harsh environmental conditions prevalent in arid and semi-arid regions, a systemised dialogue between indigenous farmer knowledge and modern technological knowledge systems is required. Some of these can be implemented at farm level, while some resources will have to be pulled together and effected from community to global level. The resource-limited farmers' ability to sustain their animals in arid and semi-arid areas and often degraded land has helped them to minimise water footprint through improved water use efficiency, utilisation of adapted breeds and feed resources (Ibidhi and Ben Salem, 2019; Salami et al., 2019; Wadhwa et al., 2015). Overall, water scarcity responses have often been reactive rather than proactive, focusing on crisis rather than risk management (Ifejika Speranza, 2010). In addition, some of the response measures comprises of foreign innovations, which in most cases fail to meet the needs and conditions of local sheep farmers.

Hence, it is important to develop a portfolio of localised recovery and resilience strategies necessary to minimise sheep farmers' vulnerability to water scarcity in arid and semi-arid regions. Table 2.1 summarises water scarcity recovery and resilience response strategies at different levels along the sheep meat value chain in dry areas.

2.7 Use of breeds tolerant to water stress

Sheep breeds differ in their ability to cope with water scarcity and subsequent stress (Schoeman and Visser, 1995; Sejian et al., 2015). Indigenous tropical breeds show greater resilience to water stress than their temperate counterparts (Mohapatra and Shinde, 2018; Schoeman and Visser, 1995; Sejian et al., 2015). Uniqueness of these breeds emanate from a combination of adaptive traits developed over time to respond efficiently to local water-scarce environmental pressures (Chedid et al., 2014; Mohapatra and Shinde, 2018). Majority of indigenous tropical sheep breeds are fat-tailed or fat-rumped (e.g. Awassi, Barbarine, Blackhead Persian, Damara, Karakul and Namaqua Afrikaner) (Alamer and Al-Hozab, 2004; Mohapatra and Shinde, 2018; Schoeman and Visser, 1995), including the South African developed composite breeds such as the Dorper and Meatmaster (Mohapatra and Shinde, 2018; Schoeman and Visser, 1995). These sheep store large amounts of fat in their tail or rump region that is mobilised to produce metabolic water (Chedid et al., 2014), which enable them to survive for up to a week with no or little drinking water (Degen and Kam, 1992; Mohapatra and Shinde, 2018).

Indigenous tropical sheep breeds exhibit unique physiological, morphological and behavioural mechanisms which allow them to cope with water stress with minimal impact on productivity (Chedid et al., 2014; Jaber et al., 2013). Behavioural mechanisms include foraging and maintaining water balance through efficient utilisation of dew obtained from foraging during the cooler hours of the day (Chedid et al., 2014; Jaber et al., 2013; Silanikove, 1992). Sheep that forage when temperatures are low, are able to minimise body water loss through their evaporative cooling mechanism (Chedid et al., 2014; Jaber et al., 2013). Also, if animals are water-stressed they tend to reduce their feed intake, a strategy which reduces heat production from fermentation, digestion and overall metabolism resulting in greater water conservation, adequate to attain a new equilibrium over a prolonged water restriction period (dos Santos et al., 2019; Jaber et al., 2013).

Table 2.1 Effect of dehydration on body weight of different sheep breeds

Breed	Physiological state	Initial body weight (kg)	Drop in LW (%)	Age (months)	Restriction/ deprivation regime	Duration (d)	Season	Temperature (°C)	Relative humidity (%)	References
Fat-tailed	Ewes	27.0 ± 1.3	3.3	24-36	50% *ad libitum* (indoors)	10	Dry	18-30	60-70	(Rahardja et al., 2011)
sheep			4.7		50% *ad libitum* (outdoors)	10		18-39.3	40-60	
Malpura	Ewes (non-	38.8 ± 0.75	0.7	24-48	Unrestricted	35	Summer	30.4-42.4	26.0-36.7	
	pregnant)		1.1		80% *ad libitum* restriction					
			3.3		60% *ad libitum* restriction					(Kumar et al., 2016)
			5.6		1-day water deprivation					
Lacaune	Ewes	55.0 ± 0.81	0.9[a]	48 ± 5	Unrestricted	28	Spring	13.5-25.8	45.6-99.3	
		55.4 ± 0.81	4.3	48 ± 5	80% ad libitum restriction					
		55.1 ± 0.81	9.6		60% *ad libitum* restriction					(Casamassima et al., 2018)
				48 ± 5						
Awassi	Lactating ewes	53.1	11.7	-	Unrestricted	21	Summer	27-31	61-85	
	and	55.9	26.2		Once every 3 days					
	Dry ewes	62.6	5.9		Unrestricted					(Hamadeh et al., 2006)
		58	16.7		Once every 3 days					
Dorper	Male (ram)	37.5 ± 0.98	16.3	6-8	4 days deprivation	18	Spring	7.7-20.5	38.9-82.7	(Degen and Kam, 1992)
Awassi	Male	58.6 ± 1.7	8.3	10-12	3 days deprivation	5 days/ season	Winter	11.3-26.7	38.3-82.3	
			12.5				Spring	12.5-28.0	717.7-70.3	
			16.0				Summer	27.7-45.7	13.6-34.3	
Najdi	Male	55.9 ± 1.9	11.4	10-12	3 days deprivation	5 days/ season				(Alamer and Al-Hozab, 2004)
			15.2							
			22.8							
Awassi	Ewes	68.5	9.5[a]	-	Unrestricted	42	Spring	15-32	54-98	
		69.5	1.2		2 days deprivation					(Jaber et al., 2004)
		65.2	5.1		4 days deprivation					
Santa Ines	Lambs	20.7 ± 2.0	-		Unrestricted	67	Dry	20.0-31.2	60.5	
				8	1-day deprivation					
					2 days deprivation					(dos Santos et al., 2019)
					3 days deprivation					

[a]-Positive weight gain for the control. NOTE: all other treatments have negative percentage gains.

Apart from behavioural mechanisms, some adapted breeds have carpet type wool and light-coloured features which protect them from solar radiation through reflection, while allowing effective cutaneous evaporative cooling, thus keeping their skin cooler relative to darker-thicker fleeces (Chedid et al., 2014; Kay, 1997). External localisation of tail fat in breeds such as the Damara, allows for less body insulation creating improved dissipation of heat from the rest of the body (Mohapatra and Shinde, 2018). Physiologically, dehydrated sheep are able to reabsorb water through thick medulla of the kidney resulting in highly concentrated urine (Chedid et al., 2014; Kay, 1997). The same re-absorptive mechanism works in large intestines by reducing faecal water losses (Chedid et al., 2014; Jaber et al., 2013). Losses are minimised, as dehydration leads to reduced passage rates, which subsequently trigger greater water reabsorption and drier faeces (Chedid et al., 2014; Jaber et al., 2013). The rumen acts as a water reservoir during water scarcity periods (Silanikove, 1992). Sheep deprived of water for 2 days will have a 2 to 3 litres rumen water volume reduction, so as to maintain normal blood osmolality (Chedid et al., 2014; Jaber et al., 2013; Kay, 1997).

Generally, indigenous tropical breeds use water efficiently because of their optimal utilisation of ingested water and feed (Araújo et al., 2010; Chedid et al., 2014; Kumar et al., 2016), and their tolerance to saline water (Castro et al., 2017; De Moura et al., 2016). Indigenous tropical sheep breeds in general exhibit better performance in adaptive traits in arid and semi-arid areas than their temperate counterparts (Mohapatra and Shinde, 2018; Schoeman and Visser, 1995). Highly productive temperate breeds are often unable to maintain their productivity under high water, heat and nutritional stress (Chedid et al., 2014; Jaber et al., 2013). Overall, stressed or diseased animals consume water and feed but do not produce expected outputs and/ or services (Descheemaeker et al., 2010). Therefore, selection, breeding and adoption of animals and breeds adapted to multiple stressors (i.e. diseases and parasites, water, heat, nutritional and walking stress) could be fundamental in reducing the water and ecological footprints (Descheemaeker et al., 2010), while maintaining acceptable levels of meat production and quality. Omics (i.e. genomic, transcriptomics, proteomics, metabolomics) and bioinformatics tools can be used to generate useful information to understand adaptation mechanisms of resilient sheep breeds (Kasper et al., 2020). For examples, the proteomic studies have been used to identify candidate proteins that responsible for the development of dark, firm and dry meat associated with pre-slaughter stress in ruminants (Fuente-Garcia et al., 2019; Kasper et al., 2020).

2.8 Use of water restriction and deprivation techniques

During the dry season, the distance between rangelands and water points are far apart such that animals travel long distances without consuming water (Alamer and Al-Hozab, 2004) (Chedid et al., 2014). In such situations, sheep can be restricted or deprived access to water so that they spend less time and energy walking to distant water points on daily basis, and thereby, increase foraging time. Water restriction involves controlled water provision for a less or more prolonged period of access (Rowland, 2007). In contrast, water deprivation involves complete water withholding for less or more prolonged period of access, mostly in multiples or submultiples of 1 day (Rowland, 2007). Tolerance by some sheep breeds to prolonged water scarcity periods allow them to maximise pasture use as animals forage far from watering points (Turner and Schlecht, 2019). Optimal water restriction or deprivation may possibly benefit animals, through efficient use of available water and feeds (Chedid et al., 2014; Jaber et al., 2013).

Implementation of either water restriction or deprivation strategies is dependent on levels of available water in a region. There are several studies conducted to explore water restriction and deprivation effects on sheep (Table 2.2). In most developing countries, little is known about water requirements and tolerance of indigenous tropical breeds to drinking limited amount of water. This is critical considering that sheep used for commercial meat production in dry environments are mostly non-adapted temperate breeds (Mohapatra and Shinde, 2018). Most producers are hesitant to use indigenous tropical breeds for meat production because of their small frame sizes and slow growth rates (Ates et al., 2015; Devendra, 2001), although they can be comparably productive to improved breeds even in high-input feeding systems (Ates et al., 2015). However, with the ever-increasing demand in meat, and the escalating water scarcity challenge in the arid and semi-arid regions, adoption of indigenous and composite breeds or their crosses with temperate breeds has potential to support sheep production for resource-limited farmers.

To the authors' knowledge, there are no recommended optimum water restriction levels and deprivation periods for sheep. Majority of studies have, however, recommended an upper limit of 20% water restriction level in adult (i.e. 2-4 years old) ewes (Casamassima et al., 2008, 2018; Kumar et al., 2016). With regard to water deprivation, Dos Santos et al. (2019) advocated for 1 day in 8-month old Santa Ines crossbred lambs over a 67-day feeding period, Al-Ramamneh et al. (2012) 21 h d^{-1} in 2-year old German Blackhead mutton ewes (for 7 days), and Jaber et al. (2004) 2 days over a one-month period in dry multiparous Awassi ewes. Overall, subjecting sheep to the recommended water restriction or deprivation levels saves water and feed, which enhances the survival of more animals in water scarce regions. For example, a farmer can save up to 1.0 litre day^{-1} adult ewe^{-1} by adopting a 20% water restriction regime (Casamassima et al., 2008, 2018) and 0.3 $litres^{-1}$ $lamb^{-1}$ day by adopting a one day water deprivation system (dos Santos et al., 2019) without compromising the animal's production performance. It is important for researchers to conduct research which will generate water requirements, optimum restriction levels and deprivation periods for different sheep ages and breeds under diverse production environments. This is important in dry environments such as Sub-Saharan Africa where the provision of fresh drinking water for animals lag behind in preference to humans (Food and Agriculture Organisation, 2012).

Table 2.2 Water scarcity recovery and resilience strategies along sheep meat production value chain in the arid and semi-arid areas

Level	Supply enhancement strategies	Water demand management strategies
Farmer/farm	- Increase supplies of water in feed through use of succulent plants; high moisture agro-industrial by-products; water stress tolerant fodder plants; xerophytic plants; hygroscopic plants; dew plants and guttation. - Increase drinking water supply through diversion of rivers; construction of water storage tanks, small ponds, dams and lakes; drilling of boreholes and wells; building of rainwater harvesting, wastewater recycling and re-use infrastructure.	- Reduce water demand through use of adapted breeds; animal genetic improvement techniques; assisted reproductive technology; water restriction or deprivation techniques; stress alleviators; conservation buffers, spreader banks, water ponding dikes, hydroponic fodder production, rotational grazing, appropriate stocking rates, feedlotting, zero-grazing; night grazing, flock mobility, trail construction, prioritisation of water allocation, off-stream watering, centripetal watering, early weaning and destocking. - Reduce water quantity and quality losses through reduction of run-off and evaporation; improved monitoring; enhanced prediction of supply; accurate leakage control; increased water use efficiency; improved feed water productivity; reduced algal growth and pollution control; farmer training in water management.
Abattoir	- Built wastewater recycling and reuse plants, water harvesting infrastructure and water storage reservoirs; improve water distribution efficiency.	- Increase water use efficiency during animal slaughter and carcass processing; improve carcass storage and distribution.
Retail	- Not applicable.	- Improve meat processing and storage; reduce meat losses and wastes; label low water footprint meat products and marketing them as niche products at premium prices.
Consumer	- Not applicable.	- Reduce meat losses and wastes; promote optimal meat consumption; advocate for changes in dietary habits; promote preference for low water-footprint meat products; use water saving meat preparation methods; provide consumer education and awareness in water scarcity and responsible consumption.
Government	- Invest in development of water supplies including water storage reservoirs; rainwater harvesting infrastructure; inter-basin transfers; wastewater recycling and reuse infrastructure; desalination plants; renewable energy infrastructure, emergence water relief systems. - Enactment and enforcement of legislation and policies that increase water supplies; promote capacitation of stakeholders; allow equitable farmers' access to water resources; ensure fair sharing of existing water resources; provide incentives that reward low water footprint; sponsor water supply; collaborative research.	- Finance water conservation infrastructure and technologies including water accounting and auditing technologies; development of water quality indicators and standards, improvement of water monitoring, modelling and prediction technologies and capacities. - Develop and enforce water saving laws and policies; gazette water rates and tariffs; provide incentives that reward low water conservation credits; develop farmer and extension training programs; youth and women empowerment; conduct public water saving education and awareness campaigns.
Funding agencies	- Finance development of water supply infrastructure, technologies, collaborative research, capacity building, legislation, policies and incentives.	- Fund water conservation infrastructure, technologies, collaborative research, capacity building, regulations, policies and incentives.

2.8.1 Sustainable management of rangelands

Several sustainable rangeland management strategies can be adopted by sheep farmers, including rangeland soil moisture conservation techniques, appropriate grazing management systems, watering point management and flock mobility (Deramus, 2004; Ncube and Lagardien, 2014). Construction of conservation buffers, spreader banks and water ponding dikes reduce water flow and allow seepage, hence remove pollutants and conserve soil moisture in rangelands (Ncube and Lagardien, 2014; Sejian et al., 2015). Grazing management is crucial in the maintenance of forage biomass and conservation of water resources. For example, use of rotational grazing in combination with appropriate stocking rates improves vegetation cover and creates a healthy and robust deep-rooted system that prevents soil erosion (Deramus, 2004). In addition, it prevents soil compaction, reduce runoff and increases soil infiltration capacity (Deramus, 2004), and ultimately improve water quality and availability (Steinfeld et al., 2006). Trails can be also built to improve livestock distribution and facilitate easy access to rangelands, and consequently minimise soil trampling and erosion (Steinfeld et al., 2006).

Where fencing is available, rotational grazing can be combined with night grazing, which allows additional time to graze forages that contain high amount of moisture at low environmental solar loads (King, 1983). The moisture can come from guttation, dew and/ or hygroscopic plants at night (King, 1983). Furthermore, use of exclusion fencing at open water points limit access by sheep and facilitate off-stream watering. Sheep flocking close to surface water points improves water quality and availability by decreasing discharge of waste and sediments into water, and trampling, which accelerate erosion (Steinfeld et al., 2006). Provision of shade and supplemental feed far away from surface water points may also reduce water pollution and soil erosion, in addition, to lowering heat and nutritional stress, respectively (Steinfeld et al., 2006). This can be accompanied by use of xerophytic plants such as the Mesquite (*Prosopis juliflora*), which reduce soil erosion, and serve as a shade, source of water and feed for the animals (Patnaik et al., 2017).

Appropriate stocking rates and off-stream watering may be implemented in combination with centripetal watering, grazing and travel mobility of flocks to manage rangeland water and feed resources (King, 1983; Turner and Schlecht, 2019). According to Ifejika Speranza (2010), flock mobility will only work if farmers are able to manage rangelands at a community level, rather than fragmenting them into individual and private tenure systems. Centripetal watering involves shepherding in grazing areas that are far away from water points at the beginning of the dry season when forages are green and weather is cool, and slowly move animals closer when forages dry and weather becomes hot (King, 1983). This prevents overgrazing of areas close to water points in the early dry season and avoid travelling long distances in search of water and feed at the peak of dry season, which coincides with time when animals' physiological status is at its lowest (Klein, 1981). Pen feeding (i.e. zero grazing) can also reduce animal movement and grazing pressure thereby saving water (Descheemaeker et al., 2010). In severe water scarce situations, farmers are recommended to practice early weaning, prioritise water allocation to breeding stock and vulnerable groups, and destock by culling low producers and selling yearlings (Ncube and Lagardien, 2014). Night grazing, guttation, dew and hygroscopic plants, flock mobility and centripetal watering concepts have not been widely adopted due to lack of evidence-based information and limited resources to implement these strategies for resource-limited farmers, thus merit further investigation.

2.8.2 Use of succulent feed resources

Sheep water requirements can be met from water in feeds, which vary from as low as 5% in dry feeds to as high as 90% in fresh grasses and legumes, forage watermelon and cactus species (Araújo et al., 2010; Cordova-Torres et al., 2017). Overall, inclusion of forage cactus in sheep diets either as fresh, silage or hay reduced water intake, and either had neutral or positive effects on rumination efficiencies and nutrient digestibility (De Sousa Nobre et al., 2018; Tegegne et al., 2007). De Abreu et al. (2019) reported that inclusion of forage cactus up to 66% improved average daily gain without compromising physicochemical and sensory quality of lamb meat. This is because forage cactus has high moisture content (850-900 g kg^{-1}), which can meet animals' water requirements (Cordova-Torres et al., 2017; De Sousa Nobre et al., 2018). The ability of cactus to maintain more water in its cells is due to mucilage presence, a hydrophilic mucus-like compound that has high water binding capacity (Tegegne et al., 2007). Apart from being a water supplement, forage cactus is high in soluble carbohydrates (251-710 g/ kg), calcium (40-80 g kg^{-1}) and α-carotene, with low CP levels (25-83 g kg^{-1}) (De Sousa Nobre et al., 2018; Tegegne et al., 2007) making it a suitable supplement for animals on low quality roughage.

Feeding high moisture agro-industrial by-products (i.e. vegetables, fruits, distillery and brewery) can reduce drinking water intake (Salami et al., 2019; Wadhwa et al., 2015). These feeds are bulk, however, and have high water activity, which makes them more susceptible to putrefaction if not preserved (Wadhwa et al., 2015). Therefore, they should be fed fresh or preserved by dehydration or ensiling for later feeding (Salami et al., 2019; Wadhwa et al., 2015). It important to note that these agro-industrial by-products have moderate CP content, high contents of fibre and bioactive compounds, which have nutritional, antimicrobial, anthelmintic and antioxidant properties that enhance animal health, meat production and preservation (Salami et al., 2019). There is scope for further research to evaluate utilisation of agro-industrial by-products and indigenous succulent plants in extensive sheep production systems, particularly their potential as sources of water, feed, stress alleviators, anthelmintics or biopreservatives.

2.8.3 Use of water stress alleviators

Water stress strains body defence systems, as it increases free radicals that induce metabolic dysfunction, and subsequently reduce animal performance (Minka and Ayo, 2007). Antioxidative compounds, including vitamins (C and E), electrolytes and sedatives have been used as commercial anti-stress agents to protect the body's defence system against production of excessive free radicals (Chedid et al., 2014; Minka and Ayo, 2007). However, affordability of these commercial anti-stress agents could be a challenge for resource-limited farmers. It is, therefore, important to find cheaper and locally available alternatives such as polyphenolic-rich plants, including indigenous and invasive alien plants, which have similar mode of action (Dezah et al., 2021; Salami et al., 2019). For example, species such as *Acacia mearnsii*, *Vachellia karroo* and *V. polyacantha* have been incorporated as protein and antioxidant supplements in diets for cattle (Chingala et al., 2019; Dezah et al., 2021; Mapiye et al., 2009) with contrasting outcomes on growth, meat production and quality. However, more research is required to determine the potential of these antioxidant-rich plants in alleviating water stress in sheep.

2.8.4 Optimisation of water use efficiency

Drinking and servicing water for the livestock sector accounts for only 0.6% of freshwater use globally with an estimated 98% used in the production of livestock feed (Peden et al., 2007). Thus, increase in water use efficiency for feed production, consequently, improves water use efficiency for livestock production and agriculture at large (Mekonnen and Hoekstra, 2012). Replacing conventional feedstocks with agro-industrial waste products (Wadhwa et al., 2015), or feed produced from water efficient crops (Ibidhi and Ben Salem, 2019) can reduce water losses. Furthermore, water use efficiency in abattoirs, processing and distribution of meat can also reduce the amount of water used along the sheep meat value chain. Abattoirs are renowned for their high-water usage and intense wastewater production (Matheyarasu et al., 2015). It is, therefore, crucial to find ways of improving water utilisation efficiency through recycling and reuse of abattoir wastewater, without reducing production. Abattoirs can develop low-cost wastewater management technologies that recycle wastewater, which can be used to convert contaminated lands into cultivable land through phytoremediation using high biomass producing plant species (Matheyarasu et al., 2015).

Development of indicators such as the water footprint, which can be used to quantify water volume required by different groups of livestock species to produce a specific product under differing feeding systems is critical for decision making and enactment of policies at provincial or national levels (Mekonnen and Hoekstra, 2012). For example, Ibidhi and Ben Salem (2019) found that agro-sylvo-pastoral farming system had the lowest water footprint. This can be used as a marketing strategy whereby products from sheep reared under such a low water footprint system can be labelled and marketed as niche products at premium prices. Zonderland-Thomassen et al. (2014) reported that consumer markets are placing a premium on products with positive environmental profiles. The same authors suggested that red meat producers should be prepared with water footprint information of their products, as consumers tend to prefer low water footprint products. Further research is warranted in this regard to evaluate water footprint of different sheep production systems in arid and semi-arid areas.

2.8.5 Sustainable harvesting and retention of freshwater resources

Sheep farmers can enhance water supply and conservation through investment in abstraction of ground water resources, rainwater and runoff harvesting infrastructure, and evaporation mitigation technologies. A substantial amount of water is largely available as underground sources such that drilling boreholes and wells can be implemented for potable provision of freshwater for sheep in times of water scarcity (Brand, 2018). This can be combined with solar or wind water pumps, thus, providing a cheaper energy source for sustainable ground water extraction, which can also be linked to pipes that provide water for sheep and humans (Manju and Sagar, 2017). Information and communications technology (ICT), global position system (GPS), geographic information system (GIS) and remote sensing technologies in combination with groundwater simulation models are viable solutions that can be used to manage this essential water resource (Mupfiga et al., 2016). However, Brand (2018) argues that the affluent often have better access to groundwater sources and often use water with little accountability, whilst the poor are hardest hit with water scarcity even if they are sitting on large water reserves. Governments should enact and enforce legislation and policies that allow equitable access to water resources to ensure adequate water supply to the resource-limited sheep farmers in the arid and semi-arid areas.

Rainwater can be collected from fields, roads, building roofs and mountains, and stored in open ponds or surface and underground tanks, and thereafter used to replenish sheep water sources during dry periods. During the rainy season, a lot of water is lost through runoff, therefore, *trans*-basin diversions and construction of ponds, dams or lakes can increase availability of drinking water for sheep in dry periods (Ncube and Lagardien, 2014). Water reservoirs should, however, be properly managed to reduce the level of algal growth and pollution, which can decrease quantity and quality of stored water (Ncube and Lagardien, 2014). The main water losses in open water sources occur through evaporation to the atmosphere, which can be minimised through physical, biological and chemical methods (Benzaghta and Mohamad, 2009; Dawood et al., 2013). Physical methods include shade structures, floating and modular covers (Benzaghta and Mohamad, 2009). In addition, water reservoir designs can be improved to minimise evaporation rates. For example, using deeper storages with smaller surface areas and dividing large storages into smaller ones reduce wind action, allowing water depth to be maximised by shifting water between cells (Benzaghta and Mohamad, 2009). Of the chemical methods available, environmentally innocuous surfactant monolayers covering water surfaces can minimise evaporation rates by as much as 40 to 70% (Dawood et al., 2013). However, this practise has low feasibility among resource-limited farmers due to prohibitive operational costs. This can, therefore, be implemented through funding from government and/ or agencies. These agencies can also assist with investments in new technologies such as GPS, GIS and remote sensing to assess sediment deposition and distribution pattern, as a result curbing storage capacity loss of many water reservoirs (Mupfiga et al., 2016).

2.8.6 Sustainable use of nonconventional water resources

Usage of nonconventional water resources (i.e. wastewater, drainage water, brackish water and seawater) has increased in many countries due to pressures imposed on current freshwater supplies (Hamdy et al., 2003). Capture and utilisation of these nonconventional water sources can reduce water scarcity for many sheep farmers, especially in peri-urban and urban areas. Large volumes of sewage and industrial wastewater are being generated annually in many water-scarce countries and discharged in places where it cannot be reused (Food and Agriculture Organisation, 2012). In developing countries, wastewater utilisation challenge is associated with potential hazards (i.e. heavy metals, biocides and microbial contamination), which can be toxic or pathogenic (Ruane et al., 2008). Another challenge is lack of infrastructure and capacity to enforce water quality standards because of its high costs and shortage of technical skills required for treatment plant operations and maintenance (Food and Agriculture Organisation, 2012). Water-scarce countries should invest more in establishment of small to large wastewater treatment plants so as to counter challenges associated with this declining resource. Hamdy et al. (2003) postulated that reutilisation of wastewater impact will be greater than other technological solutions such as water harvesting, cloud seeding, weather modification and desalination at increasing water supply.

Various technological applications are available for wastewater purification through removal of solids, heavy metals, pathogens and/ or chemical pollutants, which have social, environmental and economic consequences (Kummu et al., 2016; Ruane et al., 2008). These include water purification using nanomaterials, which can either be used as stand-alone treatment agents or incorporated into biological membranes and integrated with conventional treatment techniques. Other technologies include use of microbial cultures, which are effective at performing a particular task such as degrading specific toxins in water (Ruane et al., 2008). However, the key challenge is to exploit this biological potential more efficiently, customise and scale it for resource-limited farmers.

Apart from wastewater, seawater desalination has potential to reliably produce enough water to support populations located in coastal areas for domestic, industrial and agricultural activities (Kummu et al., 2016). Currently, desalination has been constrained by its exorbitant costs, high energy requirements and local salinity pollution (Ruane et al., 2008). However, its costs have been declining over the years, and desalinated water is becoming more competitive considering that freshwater costs are rising (Ruane et al., 2008). Governments should, therefore, consider investing in development of small- to large-scale desalination plants, which utilise clean, green and renewable energy sources such as wave, tide, solar, wind and geothermal heat (Manju and Sagar, 2017).

2.8.7 Water-saving decision support tools

Water management is an increasingly challenging issue because of the often conflicting economic, social, and cultural interests. According to Giupponi and Sgobbi (2013), involvement of citizenry and lobby groups in environmental matters, lack of coordination among stakeholders, sometimes incoherent local and international environmental policies and regulations, are factors that complicate planning and decision-making regarding management and utilisation of water resources. This requires strengthened support from scientifically robust methods and tools to assist farmers, policy makers and other stakeholders. This can be achieved through use of decision support system tools such as water accounting and auditing techniques at farm level. Water accounting involves monitoring of volumes, flows, distribution and quality of water in the environment, and the economic values of water through cost-benefit analysis (Food and Agriculture Organisation, 2012). "Water audits place water supply and demand in the broader context of governance, institutions, finance, accessibility and uncertainty" (Food and Agriculture Organization, 2012). At farm level, efficient water accounting and auditing enable farmers to know the amount of water available for the animals, its cost and their water requirements over a specific period, which can be a starting point for development of strategies to cope with water scarcity in arid and semi-arid areas.

Use of equations for predicting water intake for feedlot sheep could assist farmers to make informed choices on which breeds or how many animals to keep based on available water resources. Development of localised models is crucial for resource-limited farmers as they customise water needs for a specific breed under local conditions. Considering that much water in animal productivity involves feed production, it is important to implement smart water leakage detection and metering technology as large quantities of water are lost within the system (Britton et al., 2013). Monitoring of water quantity and quality for sheep can be complemented by integrated use of emerging techniques such as ICT, GPS, GIS, and remote sensing. In addition, use of e-extension services and mobile phone applications focusing on sharing knowledge, skills and information on agricultural water management and use efficiency among farmers empower them to make informed decisions (Thiga et al., 2018).

2.8.8 Capacity building and policy development

Most resource-limited farmers are faced with a myriad of problems, and efficient utilisation and conservation of water are usually at the bottom of their priorities (Ifejika Speranza, 2010; Opiyo et al., 2015). A study conducted by Alam (2015) in drought-prone areas revealed that farmers with enhanced farming experience, higher education levels, more secure tenure rights, greater electricity and institutional facility access, and climatic effects awareness were very likely to embrace alternate adaptation strategies. Thus, enabling access to these factors would go a long way in improving farmers' ability to deal with future water scarcity. Lack of capacity stems from skills knowledge gap among extension workers when it comes to disseminating technical information on water management. Further, the high extension worker to farmer ratio limits the interaction and information exchange interface, hence most farmers rarely get any assistance with their livestock (Baloch and Thapa, 2019). It is, therefore, fundamental to build resilience of resource-limited farmers through capacity development of extension workers as they serve as network nodes between farmers and national governments (Alam, 2015; Ifejika Speranza, 2010).

Training and capacity building activities in communities aimed at facilitating skills transfer and the use of participatory approaches involving key community stakeholders can potentially solve current and future problems with regards to water scarcity (Baloch and Thapa, 2019). Governments can train farmers to manage risks associated with water scarcity, such that this knowledge is retained within communities, thus, reducing dependence on extension and environmental officers (Ifejika Speranza, 2010). Empowering farmers, particularly youth and women through training in agricultural water management (Sejian et al., 2015) could modify water utilisation behaviour and promote voluntary and long-lasting investments in water supply enhancement and conservation strategies (Descheemaeker et al., 2010; Food and Agriculture Organization, 2012). This is important given that sheep are commonly owned and managed by women, who are more vulnerable to water and food insecurity (Devendra, 2001).

An educational program to raise public awareness of the impacts of water scarcity on current and future meat production and consumption trends will assist people to prepare and respond effectively through responsible consumption and changes in dietary habits, and enactment of relevant laws and policies (Food and Agriculture Organisation, 2012). Given that professionals are responsible for executing water scarcity response strategies, they should also receive relevant education and training. This may be done through introduction of water risk management module in agricultural curricula in colleges and universities or short in-house courses.

Efficient water resource management in arid and semi-arid areas will largely rely on established institutional and legal frameworks to address the complex issues of water supply, use and conservation (Descheemaeker et al., 2010; Food and Agriculture Organization, 2012) along the meat production-continuum. Development of a water-saving policy, which will promote water supply, use efficiency and conservation investments, issuing of water scarcity warnings to farmers, creation of guidelines on how to prevent and counteract its effects and release advisories on appropriate response strategies is important (Descheemaeker et al., 2010). An incentive system that rewards farmers for using less or conserving water should also be established. Incentives for construction of water supply infrastructure and installation of water-saving devices should be designed in ways that promote efficient use of energy and water resources.

2.9 Towards sustainable adoption of water management strategies

Several water scarcity recovery and resilience strategies and technologies have been proposed and tested by smallholder farmers in developing countries (Food and Agriculture Organisation, 2012; Zossou et al., 2020). Regrettably, adoption, scale-up and impact of climate-smart agricultural strategies and technologies in developing countries remain below expected levels, particularly among smallholder farmers in Sub-Saharan Africa (Meijer et al., 2015; Takahashi et al., 2020). This has been attributed to several factors including lack of evidence of effectiveness of new strategies and technologies, adaptive capacity, resources, and good governance (Muthelo et al., 2019). In addition, little attention has been paid to the factors that influence adoption and scaling of climate-smart agricultural strategies and technologies in developing countries spanning the spectrum from extrinsic (e.g. attributes of the innovation, adopter, and external environment) to intrinsic (e.g. knowledge, perceptions, attitudes and beliefs) and intervening (e.g. communication and extension) variables (Meijer et al., 2015; Shackleton et al., 2015).

Recent evidence is showing that use of locally available renewable natural resources, integrated water, soil, plant and animal management, stakeholder engagement in technology development and consideration of interactive contextual factors influencing decision-making promote rapid and widespread adoption of climate-smart agricultural strategies and technologies in developing countries (Meijer et al., 2015; Muthelo et al., 2019; Zossou et al., 2020). Lottering et al. (2020) further shows that adoption and scale-up rates are likely to be high if farmers have access to capital, simple and cost-effective strategies and technologies. Enhancing the role of local institutions and integrating indigenous knowledge in the planning and development of climate-smart agricultural strategies and technologies also improve their adoption and scaling success by smallholder farmers in developing countries (Takahashi et al., 2020). A better understanding of these factors that stimulate sustainable adoption and scaling of climate-smart agricultural strategies and technologies is essential in formulating effective strategies and policies that enhances smallholder sheep production, livelihoods, and environmental services in developing countries.

2.10 Conclusions

The changing global climate and projected frequent and severe droughts are likely to impact the severity of water scarcity in arid and semi-arid areas. A menu of local-level recovery and resilience strategies have been identified for adoption by water-scarce countries to alleviate the negative effects of water scarcity on sheep meat production and quality. The primary recovery strategies include use of adapted breeds, water restriction and deprivation techniques, sustainable rangeland management practices, succulent feeds, and water stress alleviators. Key resilience strategies involve investments in water supply enhancement and conservation infrastructure and technologies, decision support tools, capacity building, research, laws, policies, and incentives that optimise water use efficiency along the sheep meat production value chain. It is, however, important to evaluate sheep farmers' perceptions on drought impact and effectiveness of each of the identified recovery and resilience strategies in improving dryland sheep meat productivity in different local environments.

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CHAPTER 3 - SHEEP FARMERS' PERCEPTIONS ON DROUGHT IMPACT

The work was published in Climate Risk Management, 34, 100369

3.1 Summary

Water scarcity is amongst the major challenges threatening smallholder sheep production in subsistence-oriented communal farms in dryland areas. Local contextual factors are a prerequisite for effective policy development and optimisation of water resources management for smallholder sheep production. Two-hundred and fifty-two structured questionnaires were administered to investigate the contextual factors that influence smallholder farmers' perceived impact of water scarcity on sheep production in the dry ecozones of the Cape provinces in South Africa and identify their local response strategies. Logistic regression findings showed that a unit increase in private commercially oriented arid farms, males, education level, flock size, adapted breeds and income from livestock increased farmers' probability to perceive impact of water scarcity on sheep production. Regardless of ecozone and farm types, sheep farmers switched between water sources, provided supplementary feed and shade, used adapted breeds and alternative markets to manage the impact of water scarcity. Interventions to build resilience to water scarcity in the surveyed areas should target sheep farmers with low adaptive capacity, particularly less educated women relying on livestock income and farming with non-adapted breeds on subsistence-oriented communal farms in the semi-arid ecozone.

Keywords: Adaptive capacity, Dryland, Ecozone, Resilience, Subsistence-oriented farmers.

3.2 Introduction

Sheep production is one of the sustainable sources of food, income and socio-cultural wealth for smallholder farmers living in arid and semi-arid areas (i.e. dry ecozones) of the world (Pollot and Wilson 2009; Almeida 2011). The sustainability of sheep production in the dry ecozones is, however, greatly challenged by scarcity of drinking water, feed, and high thermal loads (Rust and Rust 2013; Molotsi et al. 2017). These stressors adversely affect sheep health, welfare, meat production and quality (Gregory 2010; Chedid et al. 2014; dos Santos et al. 2019). This subsequently reduces profit and threaten the sustainability of livelihoods dependent on sheep farming in dry ecozones.

Globally, smallholder farmers in dry ecozones are the most vulnerable to the water scarcity challenge largely due to existence of multiple stressors, lack of adaptive capacity, poor governance and little or no investments in water resources management (Gandure et al. 2013; Cosens and Chaffin 2016). Smallholder farmers generally own small pieces of land and often have low-income levels largely derived from livestock and social grants (Marandure et al. 2016; Gwiriri et al. 2019). In this regard, interventions aimed at optimising agricultural water use efficiency in dry ecozones should target smallholder farmers.

Community engagement and consideration of local contextual variables including farmers' perceptions and ecological, economic and social factors shaping them are key in promoting smallholder farmers' actions to cope with local impacts of water scarcity (Hutchings et al. 2015; Fan et al. 2019; Muthelo et al. 2019). Disregarding farmer's perceptions of the impact of natural disasters and/ or their effects on livelihoods will miss the contextual realities that are important in formulating appropriate adaptive technologies (Patt and Schröter 2008; Singh et al. 2016; Alam et al. 2017). Contextual factors influence the processes and responses smallholder farmers take to cope and/or adapt to natural hazards (Yu et al. 2013; Singh et al. 2018).

Knowledge of local perceptions and core factors influencing them is important in devising effective response strategies that enhance the sustainability of the dryland sheep production and consequently improve smallholder farmers' livelihoods (Abdul-Razak and Kruse 2017; Alam et al. 2017; Singh et al. 2018). Specifically, knowing which groups among the smallholder farmers have the lowest adaptive capacity to water scarcity and the relevant determinants for these capacities could provide the basis to unearth the most effective policy and supportive strategies. The aim of the current study was, therefore, to investigate the determinants of smallholder farmers' perceived effects of water scarcity on sheep production in the dry ecozones of the Cape provinces in South Africa and identify local response strategies.

3.3 Materials and methods

3.3.1 Study sites

Surveys were conducted in the dry ecozones of three provinces of South Africa namely, Northern Cape, Western Cape, and Eastern Cape (AgriSA 2019). Communities, local and districts municipalities within each province were selected based on aridity, sheep population and number of smallholder farmers. In the current study, a simple aridity index based solely on precipitation was used with "semi-arid ecozone" referring to an area receiving annual precipitation ranging between 250 and 500 mm and "arid ecozone" receiving less than 250 mm (IPCC 2007; Maliva and Missimer 2012). Figure 3.1 shows locations of the surveyed communities and Table 3.1 presents their meteorological, soil and vegetation data. All the surveyed communities in the Eastern Cape Province were classified as semi-arid while those in the Northern and Western Cape provinces were arid. The study received ethics approval from Stellenbosch University Humanities Research Ethics Committee (SU-HREC-10048-2019), which complies with the South African National Health Act No.61 2003 and regulations relating to research involving human participants.

3.3.2 Selection of participant smallholder farmers and data collection

A purposive sampling strategy was used to select the smallholder sheep farmers for the current study. Purposive sampling is a non-probability selection that selects a sample based on the characteristics of the population and the objective of the research study. The study population was selected based on sheep ownership and agro-ecological zone (i.e. semi-arid and arid regions). In each community, a list of smallholder farmers owning sheep obtained from the local Department of Agriculture, Land Reform and Rural Development extension office was used as a sampling frame. Subsequently, a random sample of 252 household heads willing to participate in the study was drawn. A prototype of the questionnaire was drafted and subsequently pre-tested in June 2019 before being revised and administered between September and November 2019. Household heads were interviewed face-to-face using a structured questionnaire administered in the local languages (i.e. IsiXhosa or Afrikaans) by trained enumerators.

The questionnaire sought information on smallholder farmers' socio-economic attributes, sheep flock structure, breeds and performance, feeding, drinking water, breeding, health and marketing management, supply and quality of drinking water for sheep using close-ended questions. Farmers' reasons for keeping sheep, water scarcity adaptation and mitigation strategies were collected using open-ended questions. Farmers' perceptions of impact of water scarcity on drinking water supply and quality, production and marketing of sheep in the past five years (2015-2019) were captured using specific questions on a 3-point Likert scale.

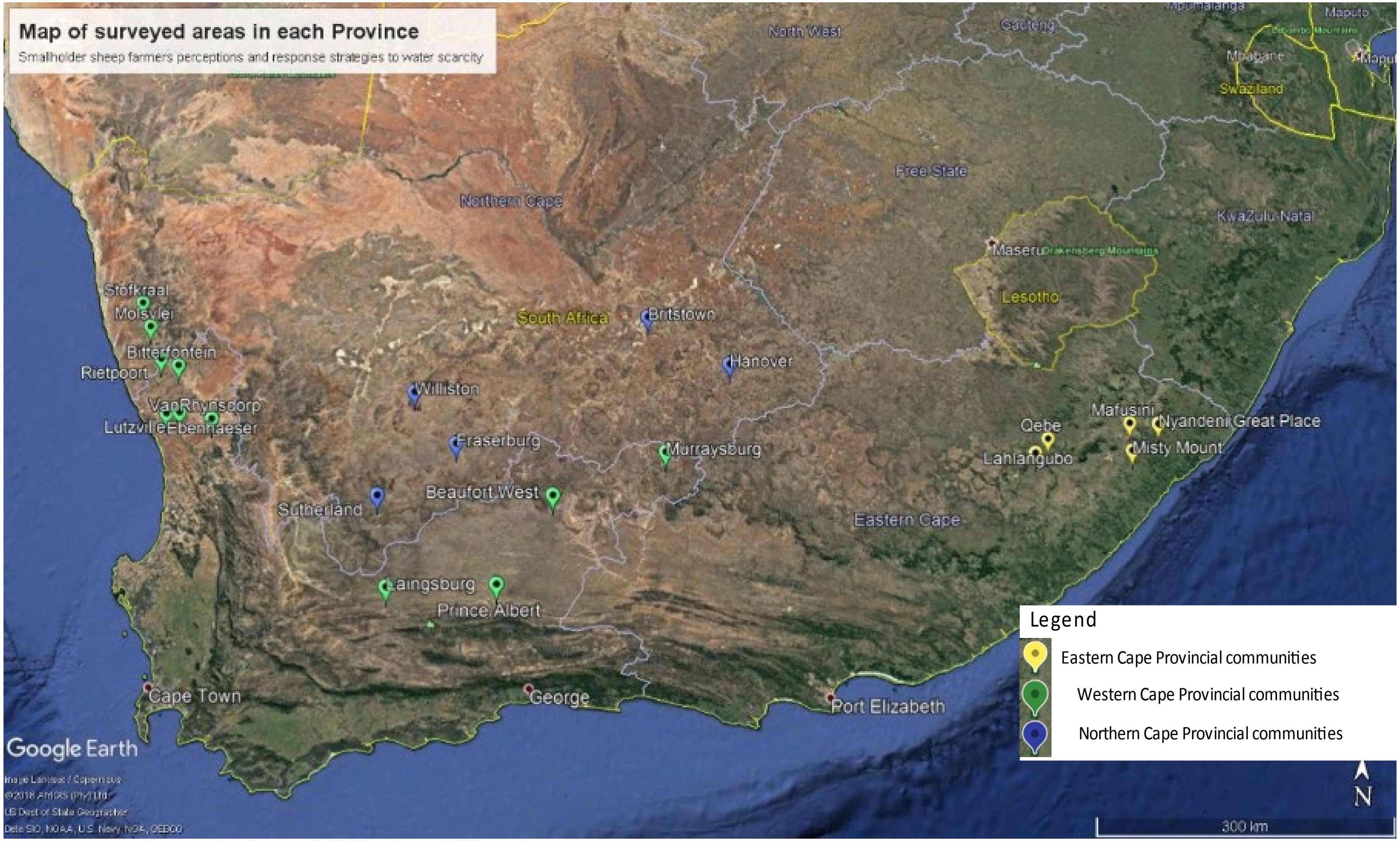

Figure 3.1 Map of surveyed communities in the dry ecozones of the Cape Provinces in South Africa

Table 3.1 Environmental conditions and sample size of surveyed areas in the dry ecozones of the Cape Provinces in South Africa

Province	**District and Local Municipality**	**Local municipality meteorological profile**		**Ecozone**	**Vegetation type**	**Soil type**	**Altitude (m)**	**Community**	**Respondents**
		Annual rainfall (mm)	Mean annual temperature (°C)						
Eastern Cape	Chris Hani - Engcobo	300-400	11-14	Semi-arid	Grassland (grasses)	Grey-like Podzolic soils	600-1500	Lahlangubo	44
								Upper Qebe	25
	OR Tambo - Nyandeni	470-550	17-20	Semi-arid	Grassland (grasses)	Grey-like Podzolic soils	450-900	Mafusini	25
								Misty Mount	5
								Nyandeni Great Place	24
Northern Cape	Namakwa - Karoo-Hoogland	100-200	17-18	Arid	Nama-Karoo Biome (grasses and dwarf shrubs)	Solonetzic Alkali soils	500-2000	Fraserburg	6
								Williston	15
								Sutherland	9
	Pixley Ka Seme - Emthanjeni	190-260	13-14	Arid	Nama-Karoo Biome (grasses and dwarf shrubs)	Desert soils	1000-1400	Britstown	14
								Hanover	23
Western Cape	West Coast - Matzikama	30-260	17-18	Arid	Succulent Karoo (succulent plants)	Desert soils	120-1260	Ebenhaeser	6
								Lutzville	8
								Stofkraal	5
								Rietpoort	6
								Molsvlei	6
	Centre Karoo - Beaufort West	150-200	17-18	Arid	Succulent Karoo (succulent plants)	Solonetzic Alkali soils	400-1000	Laingsburg	8
		170-235	17-18	Arid	Nama-Karoo Biome (grasses and dwarf shrubs)	Solonetzic Alkali soils	400-1000	Beaufort West	10
								Murraysburg	8
								Prince Albert	5

Sources: https://www.climatedata.eu/; https://en.climate-data.org/; https://www.worldweatheronline.com/

3.3.3 Validity and reliability of data

To ensure face, content, construct and criterion validity of the survey data, a questionnaire was developed based on established theories (Taherdoost, 2016; Aithal and Aithal, 2020). The Cronbach's alpha using the ALPHA option in PROC CORR of Statistical Analysis System (SAS) version 9.4 (SAS Institute 2012) was conducted to test the reliability of the data. When the reliability coefficient for the pre-test and the administered questionnaire was above 0.7, the data was considered reliable (Mohajan, 2017).

3.4 Statistical analyses

All data were analysed using SAS Institute Inc. (2012). Household heads' and farm information were subjected to descriptive statistics using the PROC FREQ procedure. Chi-square test was used to determine the association between contextual (i.e. ecological and socioeconomic) factors and effects of water scarcity on drinking water supply and quality, sheep production and marketing. The roles of sheep and factors limiting the implementation of water scarcity response strategies were analysed using Kruskal-Wallis test (NPAR1WAY procedure). Flock structure data were analysed using the PROC GLM procedure with ecozone, gender of the household head and their interaction as the fixed effects and farmer as random effect, respectively. Treatment means were generated and separated using the LSMEANS and Tukey's adjustment for multiple comparisons, respectively. Statistical significance was declared at $P \leq 0.05$.

Ecological and socio-economic factors influencing smallholder farmers' perceptions of the impact of water scarcity on sheep production and meat quality were analysed using multivariate ordered logit. The model predicted log odds of being at a cut-off point versus being at a lower or higher category of the ordered outcomes (Fullerton 2009). The core dependent ordered variables were farmers' responses to the impact of water scarcity on drinking water supply and quality, sheep production and marketing coded: 1 = decreased, 2 = increased and 3 = constant (no change). Ecological and socio-economic factors were the independent variables (determinants). The data set for independent variables was reorganised into a binary mode. The model included independent variables whose maximum likelihood estimates converged only and had non-significant score test for proportional odds assumptions. Selection of independent variables that were incorporated in the model was done using the forward selection model option embedded in PROC LOGISTIC procedure SAS Institute Inc. (2012). The ordered logit model used is as follows:

$$Log\left(\frac{\Pr(Y\ \leq\ m\mid x)}{\Pr(Y\ <\ m\mid x)}\right)=\ \tau m-x\beta(1\ \leq m\ <M)$$

where, m = category (ordered category: 1 = decreased, 2 = increased and 3 = constant); x = effect of the determinant of farmer's perception outcomes; τ = cut-off point; β = vector of logit coefficients; τm = log odds of being in category m or a lower versus a higher category (M) where the ordering of cut points was constrained to $\tau 1 < \tau 2 \ldots < \tau M-1$. Findings were reported as logit coefficients estimate of being at a cut-off point versus being at a lower or higher category of the ordered outcomes. A negative logit coefficient estimate denotes that the category was lower than the cut-off point whereas a positive logit coefficient estimate showed that the category was higher than the cut-off point.

3.5 Results and discussion

3.5.1 Profile of the participants

Gender and religion of the household heads were associated with ecozone ($P \leq 0.05$). Male participants (86%) in the arid ecozone were more than those in the semi-arid ecozones (59%). More than half of the respondents were aged between 50 and 70 years, and either had primary or no formal education. There were more Christian respondents (94%) in the arid ecozone than in the semi-arid ecozone (77%). Traditionalists (20% of the respondents) were only found in the semi-arid ecozone. Most respondents (67%) from the surveyed areas acknowledged that livestock was their major source of income followed by social grants (35%) and pension (33%), respectively. All the farmers in the semi-arid ecozone were subsistence farmers on communal land, while those in the arid ecozone were commercially oriented famers on private land (formerly referred to as emergent farmers). Farmers in the arid ecozone had larger ($P \leq 0.05$) land sizes than those in the semi-arid ecozone (1678 ± 178.8 vs 205 ± 128.9 ha).

3.5.2 Sheep flock structure, production parameters and breeds

Farmers in the arid ecozone had greater ($P \leq 0.05$) ewe, lamb and total sheep numbers than those in the semi-arid ecozone (Table 3.2). Sheep ram numbers, water and feed intakes, lambing percentage and interval, milk yield and meat prices were similar ($P > 0.05$) across ecozones (Table 3.2). Sheep mature body weight, number of lambs weaned and age at first lambing were greater ($P \leq 0.05$) in the semi-arid ecozone while number of lambs born alive, sheep mortality and sales were lower ($P \leq 0.05$) than those in the arid ecozone (Table 3.2). In addition to sheep, some farmers in the surveyed ecozones kept chickens (24% of the respondents), goats (23%), cattle (13%) and pigs (6%).

Sheep breed ownership, preferences and reasons for breed preferences differed ($P \leq 0.05$) between the ecozones. Dorper was the most common breed in the arid ecozone (67% of the respondents), followed by Meatmaster (15%), Merino (13%) and Damara (5%) with breed preference following the same trend. In the semi-arid ecozone, non-descript crossbreds (27% of the respondents) were dominant followed by Dorper (18%), Dohne Merino (17%), Merino (14%), Damara (9%), South African Mutton Merino (SAMM, 9%), Meatmaster (3%) and Dormer (3%). However, most respondents in the semi-arid ecozone preferred farming with Merino (26% of the respondents), SAMM (22%) and Dohne Merino (19%). In the arid ecozone, the breed preference was driven by adaptability to local environmental conditions (58% of the respondents), whereas high meat and wool productivity (41%) were the key preference drivers in the semi-arid ecozone.

3.5.3 Production objectives and practices

Cash income was main reason for keeping sheep as mentioned by about 80% of the interviewed farmers (Fig 3.2). Other reasons for keeping sheep varied with ecozone (Fig 3.2). For example, respondents in the arid ecozone ranked meat and flock building as the second and third most important reasons for keeping sheep, whereas those in the semi-arid ecozone ranked wool and meat, respectively. There were more ($P \leq 0.05$) farmers in the semi-arid ecozone using sheep for wool, culture, festivities, and manure than those in the arid ecozone (Fig 3.2).

Most farmers in the arid (60%) and semi-arid (93%) ecozones practised extensive farming system with rangelands as the main feed resource. Majority of farmers in the semi-arid ecozone (95%) practised continuous grazing compared to those arid ecozone (50%; $P \leq 0.05$). All farmers in the arid zone practised supplementary feeding in the dry season compared to 65% in the semi-arid ecozone. Regardless of the ecozone, farmers used maize, commercial pelleted feed and molasses concentrates, crop harvest residues, Lucerne and grass hay as supplementary feeds for sheep. Famers in the arid ecozone supplied sheep with water whereas those in the semi-arid ecozone were left to fend for themselves. Overall, uncontrolled mating was practised by most farmers in the arid (65%) and semi-arid (100%) ecozones. Kraals were the most common type of housing in the arid (66% of respondents) and semi-arid (90%) ecozones. Farmers in the arid zone marketed sheep formally through auctions and abattoirs while those in the semi-arid zones marketed informally to local consumers and middlemen.

Table 3.2 Sheep flock structure and production parameters (least square mean ± standard error) in the dry ecozones of the Cape Provinces in South Africa

Parameters	Ecozone		P-value
	Arid	Semi-arid	
Number of ewes	$42.8^{a} \pm 5.48$	$28.8^{b} \pm 4.35$	0.047
Number of rams	3.50 ± 0.74	3.60 ± 0.59	0.916
Number of lambs	$40.6^{a} \pm 7.39$	$25.8^{b} \pm 3.55$	0.018
Flock size	$85.6^{a} \pm 12.5$	$56.1^{b} \pm 10.1$	0.048
Water intake per animal per day (L)	5.68 ± 0.60	5.73 ± 0.52	0.9482
Feed intake per animal per day (kg)	4.55 ± 0.88	5.77 ± 0.72	0.2804
Mature sheep weight (kg)	$52.0^{b} \pm 2.24$	$59.2^{a} \pm 1.97$	0.0161
Lambs born alive per ewe per annum	$1.41^{a} \pm 0.05$	$1.13^{b} \pm 0.04$	<.0001
Lambing percentage	88.4 ± 2.31	87.2 ± 1.90	0.6972
Lambs weaned per ewe per annum	$53.5^{b} \pm 2.82$	$65.0^{a} \pm 2.27$	<.0001
Lambing interval (months)	10.2 ± 0.35	10.2 ± 0.29	0.9725
Age at first lambing	$16.2^{b} \pm 0.76$	$21.6^{a} \pm 0.61$	<.0001
Milk yield per ewe per day (L)	1.35 ± 0.17	0.96 ± 0.17	0.1269
Mortality per annum	$6.24^{a} \pm 0.80$	$3.91^{b} \pm 0.61$	0.0220
Sheep sales per annum	$18.1^{a} \pm 2.77$	$9.39^{b} \pm 2.18$	0.0144
Sheep meat price per kg	147.4 ± 55.1	148.1 ± 44.27	0.9340

[a-b] Least square means with different superscripts in the same row are significantly different ($P \leq 0.05$).

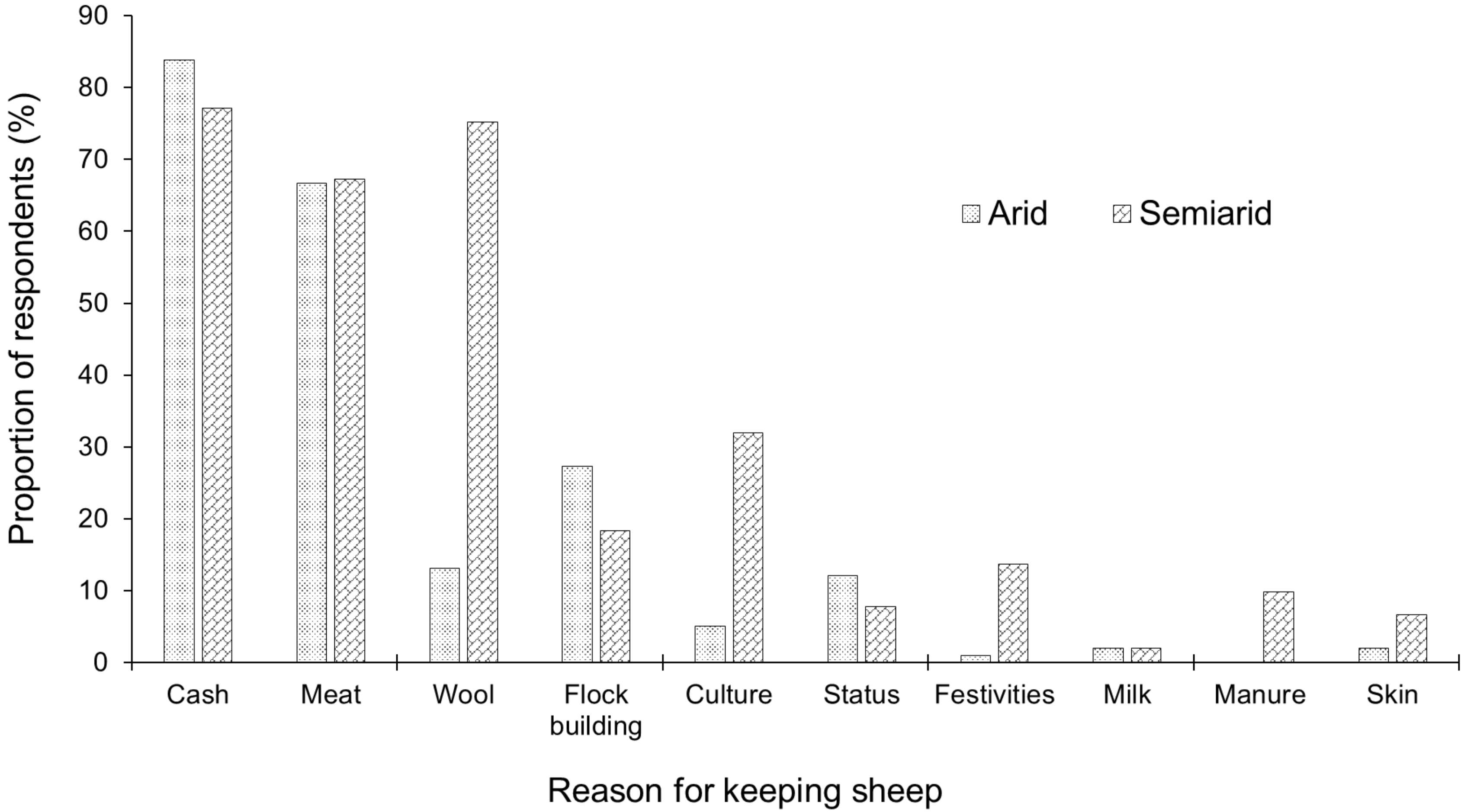

Figure 3.2 Proportion of smallholder farmers reporting reasons for keeping sheep in the dry ecozones of the Cape Provinces in South Africa

3.5.4 Perceived impacts of water scarcity on sheep production

There were more farmers ($P \leq 0.05$) on subsistence-oriented communal farms in the semi-arid ecozone (85% of the respondents) who experienced water scarcity than those on commercially oriented private farms in the arid ecozone (64%). Low rainfall was mentioned as the major reason causing water scarcity on commercially oriented private farms in the arid ecozone (44% of the respondents) and subsistence-oriented communal farms in the semi-arid ecozone (75%).

A unit change from subsistence-oriented communal farms in the semi-arid ecozone to commercially oriented private farms in the arid ecozone increased the likelihood of farmers' water scarcity impact perceptions for cleanliness and safety of drinking water for sheep, mortality, disease and parasite prevalence and sheep prices by percentage points ranging from 0.5 to 0.9 (Table 3.3). The observation that a unit change from communal subsistence-oriented semi-arid farms to private commercially-oriented arid farms increased the likelihood of farmers' water scarcity impact perceptions for water quality, sheep production and marketing attributes could be related to the differences in farmers' resources ownership, type of breeds kept, farm management practices and climatic conditions. By virtue of their private land tenure, large land size and more financial resources, commercially oriented private farms are less vulnerable to water scarcity than subsistence-oriented communal farms with small farmland and limited financial resources (Aguilar et al., 2021; Gandure et al., 2013; Mapiliyao et al., 2012; Opiyo et al., 2015).

Previous findings reported that farmers with larger land sizes have greater capacity to diversify and invest in climate change and water resource management infrastructure and technologies than those with small land sizes (Abdul-Razak and Kruse, 2017; Ali and Erenstein, 2017; Defiesta and Rapera, 2014). Relative to commercially oriented farmers on private land, subsistence-oriented farmers on communal land rely on temporary surface water sources (i.e. streams and rivers; Mdletshe et al., 2018; Mthi and Nyangiwe, 2018; Nguyen et al., 2016). Temporary surface water sources run dry in the dry season and are insufficiently protected compared to ground water (Sasakova et al., 2018) and thus more prone to contamination by physical debris, dissolved materials and pathogens making the water dirty and unsafe to drink (Sharma and Bhattacharya, 2017). The reported influence of ecozone and farm typology on farmers' perceptions of the impact of water scarcity on prices of live sheep may be attributed to differences in costs of production (e.g. water, feed, and drugs) and marketing. Commercially oriented farmers often market their sheep formally through auctions and abattoirs and incur more transaction costs (e.g. transportation, communication, and legal costs) than subsistence-oriented farmers who market their animals informally to local consumers and middlemen (Khapayi and Celliers, 2016; Mapiliyao et al., 2012; Morakile et al., 2021).

The reasons for observed change in ecozone and farm typology with increased perceptions of the impact of water scarcity on sheep mortalities, disease and parasite prevalence might be linked to differences in climatic conditions and farmer resource possessions. Warm and moist conditions prevalent in the semi-arid ecozones are favourable for proliferation of disease pathogens and parasite vectors (Marufu et al., 2011; Meissner et al., 2013; Rust and Rust, 2013). Furthermore, the non-adapted breeds (i.e. exotic and non-descript crossbreds) kept by subsistence-oriented communal farmers tend to carry heavy parasite loads, which often results in high mortality due to lack of financial resources to pay for medicines, vaccines, extension and veterinary services bills (Mapiliyao et al., 2012; Mpofu et al., 2020). In addition, continuous grazing commonly practised in the communal areas consistently expose animals to a combination of pathogenic, thermal, nutritional and water stresses (Kumar et al., 2013; Rapiya et al., 2019).

The finding that changes in ecozone and farm typology jointly influenced smallholder farmers' perceived impact of water scarcity on sheep drinking water quality and marketing could also be attributed to poor management practices that was reported in communal subsistence-oriented semi-arid farms (Mapiliyao et al., 2012). These practices include uncontrolled communal rangeland grazing and mating, poor management of water resources, animal health and marketing, which all negatively affect sheep productive performance (Ben Salem, 2010; Gowane et al., 2017; Mdletshe et al., 2018). The marginal effect of farmers' perceptions of the impact of water scarcity on the number of lambs weaned was likely to decrease ($P \leq 0.05$) by 0.4% for every one percent change from communal subsistence-oriented farming in the semi-arid ecozone to private commercially oriented farming in the arid ecozone. Farm typology and ecozone did not influence ($P > 0.05$) farmers' perceived impact of water scarcity on water sources, distance to water sources, age at first lambing, number of lambs born alive, lambing percentage, number of lambs weaned, lambing interval, milk yield, mature sheep weight, carcass fatness, sheep prices and sales.

The possibility of farmers to perceive the impact of water scarcity on distance to water sources and lambing percentage, respectively, increased ($P \leq 0.05$) by 0.8 and 0.6% with one percent increase in non-adapted breeds (Table 3.3). Adapted breeds such as Dorper and Meatmaster that were dominant on commercially oriented private farms in the arid ecozone have long, slim legs, which allow them to walk long distance (Milne, 2000; Mohapatra and Shinde, 2018; Molotsi et al., 2020), and produce more lambs than non-adapted breeds (Molotsi et al., 2017; Schoeman, 2000), respectively. Contrary, majority of subsistence-oriented communal farmers in the semi-arid arid ecozone owned exotic breeds and non-descript crossbreds, which are less adapted to their socio-economic and environmental conditions. This concurs with the current results indicating that farmers who farmed with non-adapted breeds had high probability of perceiving increases in distances to water sources and decreases in lambing percentages over the past five years. Furthermore, subsistence-oriented communal farming is associated with uncontrolled mating which often result in inbreeding depression (Gizaw et al., 2014), and failure to synchronise lambing with growing season when vegetation is sufficient to meet nutritional requirements for the lactating ewes and their lambs (Ercanbrack and Knight, 1991; Van Wyk et al., 2009).

One percent rise in male participants increased ($P \leq 0.05$) farmers' chances to perceive impact of water scarcity on water safety, number of lambs weaned and milk yield by 0.1, 0.9 and 0.8 percentage points, respectively (Table 3.3). The positive association between gender and farmer perceptions of the impact of water scarcity on sheep drinking water safety, number of lambs weaned, and milk yield was expected. Relative to female-headed households, male-headed ones have more access to information, resources, technologies, and socioeconomic opportunities (Abdul-Razak and Kruse, 2017; Ali and Erenstein, 2017; Asrat and Simane, 2018; Singh et al., 2018) that may positively influence water quality, weaning rates and milk yield. The likelihood of farmers to perceive the impact of water scarcity on water cleanliness, milk yield and sheep prices correspondingly increased ($P \leq 0.05$) by percentage points of 0.3, 0.6 and 0.9 with a unit enhancement in education level (Table 3.3). The finding that a unit increase in education level of the household head increased farmers' perceived impact of water scarcity on water cleanliness, milk yield and sheep prices was anticipated. Education has been reported to increase farmers' perceptions regarding climate change due to its contribution to increased production and marketing efficiency and adoption of appropriate technologies (Asrat and Simane, 2018; Deressa et al., 2009; Fierros-González and López-Feldman, 2021).

For every one percent growth in income from livestock, the probability of farmers' perceptions of impact of water scarcity on cleanliness and safety of drinking water for sheep increased ($P \leq 0.05$) by 0.4 and 1% in that order (Table 3.3). The observation that farmers' perceptions of the impact of water scarcity on drinking water quality for sheep was positively affected by the source of income of the household head could be related to the livestock farmers' ability to prioritise investment in water resource management technologies and infrastructure to secure their livestock-based livelihoods (Abafita and Kim, 2014; Asrat and Simane, 2018). A unit increase in flock size was likely to increase ($P \leq 0.05$) farmers' perceptions of the impact of water scarcity on milk yield by 0.4 percentage points (Table 3.3). The result that a unit increase in flock size increased the probability of farmers to perceive impact of water scarcity on milk yield was attributed the strong correlation between these two variables. Large flocks produce more milk for lambs, human consumption, and sales, which could reduce farmers vulnerability to water scarcity (Gemechu et al., 2016; Sani and Kemaw, 2019). Age did not influence ($P > 0.05$) farmers' perception of the impact of water scarcity on all the dependant variables included in the logit model.

3.5.5 Farmers' responses to impacts of water scarcity on sheep production

Most farmers, irrespective of ecozone and farm typology switched between water sources, used off-farm water sources, harvested rainwater into storage tanks and drilled boreholes or wells to increase drinking water availability for their sheep (Fig 3.3). There were more farmers on commercially oriented private farms in the arid ecozone who used clean water sources, covered, and shaded water points to cope with the challenge of declining water quality than those on subsistence-oriented communal farms in the semi-arid ecozone ($P \leq 0.05$; Fig 3.3). Majority of farmers on commercially oriented private farms in the arid ecozone provided supplementary feed, water and shade and used adapted breeds to cope with the negative effects of water scarcity on sheep production than those on subsistence-oriented communal farms in the semi-arid ecozone ($P \leq 0.05$; Fig 3.3). To cope with negative impacts of water scarcity on sheep marketing, most farmers on commercially oriented private farms in the arid ecozone explored alternative marketing channels and provided supplementary feeds whilst those on subsistence-oriented communal farms in the semi-arid ecozone withheld sales, reduced prices for live sheep and meat, and waited for the festive season ($P \leq 0.05$; Fig 3.3).

Farmers provided a menu of response strategies including management of water, feed, and animal resources to mitigate adverse effects of water scarcity on sheep production. That information could form the basis for formulating effective water scarcity policies for smallholder sheep farmers in the surveyed areas. Such policies should focus on enhancing the resilience and adaptive capacity of smallholder sheep farmers through provision of capital to purchase production inputs, improve information and communication technologies, develop water infrastructure and technologies, and establish water resource management training institutions as mentioned by the farmers in the current study.

Table 3.3 Marginal effects on the determinants of farmers' perceptions of the impact of water scarcity on sheep production in the smallholder dryland areas of South Africa

Independent variables	Dependant variables	Margin	Standard error	z	P>|z|	[95% Conf. Interval]	
	Water cleanliness	0.004637	0.000796	5.82	0.001	0.003076	0.006192
	Water safety	0.005633	0.001688	3.34	0.001	0.002325	0.008944
	Number of lambs weaned	-0.004214	0.000417	10.1	0.001	0.005031	0.007338
Farm typology and ecozone	Mortality	0.004637	0.079651	5.82	0.001	0.030759	0.061824
	Disease prevalence	0.006226	0.001726	3.61	0.001	0.006119	0.009282
	Parasite prevalence	0.008808	0.010313	2.85	0.393	0.290218	0.314050
	Sheep prices	0.005655	0.017413	3.25	0.001	0.022429	0.090683
Gender	Water safety	0.001457	0.000476	3.06	0.002	0.003689	0.004243
	Number of lambs weaned	0.008515	0.009561	2.55	0.003	0.005412	0.006158
	Milk yield	0.007720	0.005549	3.19	0.001	0.002351	0.004132
Education level	Water cleanliness	0.002543	0.000462	3.37	0.007	0.007158	0.009561
	Milk yield	0.005518	0.001723	3.19	0.001	0.012284	0.036762
	Sheep prices	0.009287	0.004812	4.60	0.006	0.000461	0.006226
Source of income	Water cleanliness	0.004118	0.002438	1.69	0.006	0.012856	0.023250
	Water safety	0.009568	0.001270	2.25	0.003	0.001244	0.00306
Flock size	Milk yield	0.004357	0.003476	3.06	0.002	0.003268	0.00512
Breed	Distance to water source	0.008446	0.002578	3.11	0.001	0.001803	0.00359
	Lambing percentage	0.005841	0.002133	1.98	0.027	0.002841	0.00400

* $P \leq 0.05$.

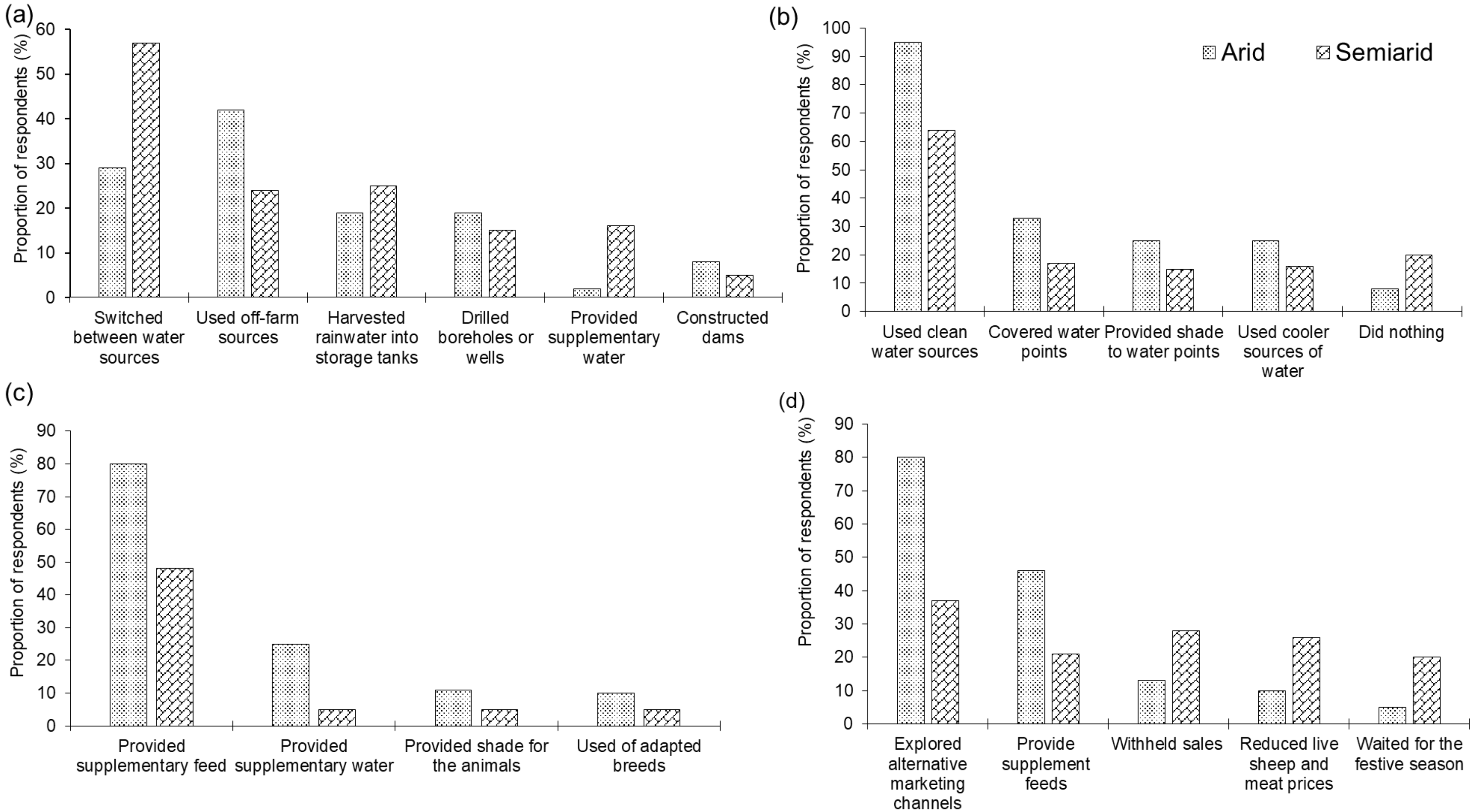

Figure 3.3 Response strategies used by smallholder farmers to cope with decreases in (a) water availability, (b) water quality, (c) sheep production and (d) marketing in the dry ecozones of the Cape Provinces in South Africa.

3.5.6 Water scarcity response strategies implementation barriers and solutions

More respondents in the semi-arid ecozone cited shortage of land followed by a lack of capital, information, infrastructural and institutional support, respectively, as the main barriers to implementation of water scarcity response strategies compared to those in the semi-arid ecozones ($P \leq 0.05$; Fig 3.4). Solutions to the implementation of water scarcity response strategies were not associated with ecozones ($P < 0.05$; Fig 3.4). Generally, farmers mentioned development of water infrastructure, water management training workshops and provision of adapted sheep breeds as potential solutions to water scarcity challenges (Fig 3.4). Current results highlight the importance of integrating smallholder farmers' perceptions of impact of water scarcity on sheep production into agricultural water resource management policies. In addition, they inform formulation of resilience strategies by providing evidence that ecological and socioeconomic variables interact to shape smallholder farmers' perception of impact of water scarcity, and vulnerability, which is consistent with previous climate change studies (Abdul-Razak and Kruse 2017; Ali and Erenstein 2017; Singh et al. 2018).

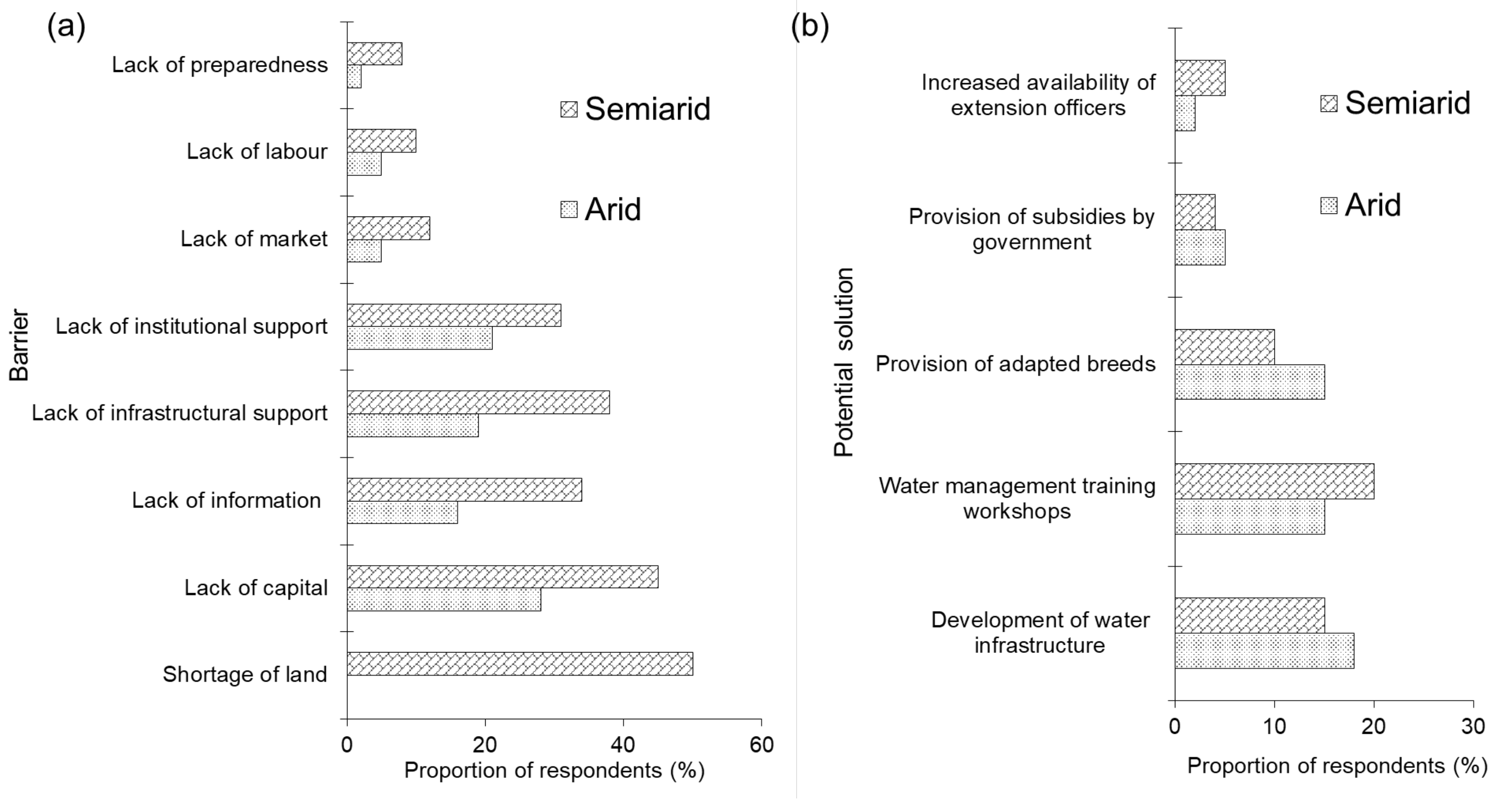

Figure 3.4 Water scarcity response strategies implementation (a) barriers and (b) potential solutions reported by smallholder farmers in the dry ecozones of the Cape Provinces in South Africa

3.6 Conclusions

Findings indicate that the likelihood of farmers to perceive the impact of water scarcity on sheep production increased with a percent increase in private commercially oriented arid farms males, education level, adapted breeds and flock size. Households responded to water scarcity through adopting a diverse array of response strategies including switching between water sources, provision of supplementary water, feed, and shade, use of adapted breeds and alternative markets irrespective of ecozone and farm types. Overall, current findings identified contextual factors determining farmers' perceptions of impacts of water scarcity on sheep production and local response strategies, which should be considered when formulating resilience and adaptive capacity enhancing technologies and policies for smallholder farmers in dry ecozones. These results highlight the importance of integrating farmers' perceptions of impact of water scarcity on livestock production and local response strategies into agricultural water resource management policies. In addition, they inform mainstreaming of climate resilience into extension and policy by further providing evidence that ecological and socioeconomic variables interact to shape farmers' perception of impact of water scarcity and vulnerability.

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CHAPTER 4 - WATER REQUIREMENTS, MEAT PRODUCTION AND QUALITY OF SOUTH AFRICAN SHEEP BREEDS

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4.1 Summary

Production of sheep is a major economic activity in the arid and semi-arid areas of South Africa. Sheep meat production in these dryland areas is, however, severely challenged by water scarcity. Since sheep genetics predefine meat production and quality traits, producers have to increase production of locally adapted sheep genetic resources to cope with water scarcity. However, little is known regarding variation in water requirements and meat production qualities among South African sheep breeds. Digestibility, water intake and growth trails were, therefore, conducted to compare digestibility, water requirements, production performance, and meat quality attributes of one exotic (Merino), two indigenous (Pedi and Damara) and three composite (Dohne Merino, Dorper and Meatmaster) South African sheep breeds. The study showed prominent differences among South African sheep breeds. Meatmaster had the highest water and dry matter intakes whilst Pedi had the least. Meatmaster and Damara had comparable water balance to Dohne Merino and Dorper, but they had superior nutrient intake, DM digestibility and N balance. Average daily gain was higher for Damara and Meatmaster compared to other breeds. Pedi and Damara had superior water intake to weight gain and feed conversion ratios whereas Dohne Merino had inferior ratios. Dressing percentage, slaughter and carcass weights were highest for Dorper, Dohne Merino and Meatmaster whilst Damara and Pedi had the lowest values. Income over feed costs were in the order of Dohne Merino > Meatmaster > Merino > Dorper > Damara > Pedi. Dohne Merino had the highest intramuscular fat while Damara and Pedi had the least with the latter having a more desirable fatty acid profile than the other breeds. Minor and inconsistent breed effects were reported for meat shelf-life and sensory attributes. Meat lightness increased over time with Pedi having the highest values on day 7 of retail display followed by the Merinos. On day 7, Dohne Merino and Merino meat had the highest lipid oxidation values while Damara and Pedi had the lowest values. The lowest meat protein oxidation values on day 7 were noted for the Meatmaster followed by Dohne Merino. Dohne Merino and Merino meat had slightly higher tenderness and juiciness compared Damara and Dorper meat. It was concluded that though Meatmaster and Dorper had somewhat lower economic returns than Dohne Merino, the most common feedlot breed in South Africa, they had comparable meat production qualities and better water utilisation efficiency making them suitable feedlot breeds in water-scarce areas. Damara and Pedi had inferior carcass attributes and economic returns, but were the most water and feed efficient breeds, which makes them breeds of choice under extreme water scarcity conditions, particularly for smallholder producers. Overall, the observed differences in water intake, growth and carcass attributes presents an opportunity for selective breeding and further development of feedlot sheep breeds to cope with water scarcity. Current findings could also enable farmers to adopt production systems and target markets that match with the breed of their choice.

Keywords: Meat production, South African sheep breeds, Water intake, Water scarcity.

4.2 Introduction

Sheep are a key source of food and income, particularly for producers in the arid and semi-arid areas of South Africa (Molotsi et al., 2020; Akinmoladun et al., 2019). Currently, the national flock stands at about 22 million, which is 10% less compared to ten years ago (DAFF, 2019). The decline in sheep numbers has mainly been attributed to water scarcity (Chikwanha et al., 2021; DAFF, 2019). Prolonged water scarcity consequently reduces availability and intake of drinking water resources (Adeniji et al., 2020; Nardone et al., 2010). Inadequate drinking water intake triggers decreases in growth and reproductive rates, immune function, and meat quality (Chedid et al., 2014; Gregory, 2010; Jaber et al., 2013). In response to these effects, a variety of local adaption and mitigation strategies spanning the spectrum from management of water, feed and animals to human resources capacitation have been adopted (Chikwanha et al., 2021). Increased utilisation of locally adapted sheep genetic resources is one of the available water scarcity coping strategies that hold the most potential (FAO, 2007).

Meat production potential of a sheep is predetermined by its genetics that interacts with environmental factors, particularly nutrition to reach full potential (Gebreselassie et al., 2020; Zhang et al., 2013). Though a sheep's specific genetic makeup is unique to that individual animal, many important meat production and quality traits are shared within breeds and bloodlines (De Lima Jùnior et al., 2016; Hopkins et al., 2011). In that regard, diverse sheep breeds present different adaptability to variable environmental and management conditions (Hopkins et al., 2011; Molotsi et al., 2020). Thus, appropriating the best available biological types of sheep to proper watering regimes has great potential to optimise meat production and quality (Chedid et al., 2014; Gaughan et al., 2019; Chikwanha et al., 2021). This could also reduce water-associated production costs and promote commercialisation of the neglected and underutilised indigenous sheep breeds. In future, markets will place a premium on animal products with a low water footprint giving them a comparative advantage over products with high water footprints (Mekonnen and Hoekstra, 2012).

South Africa has about 23 known sheep breeds with the Dohne Merino, Dorper, South African Mutton Merino (SA Mutton Merino) and Meatmaster being the most common composite breeds, while Damara and Blackhead Persian, and Merino and Ile de France are the dominant indigenous and exotic breeds, respectively (Cloete & Olivier, 2010; Molotsi et al., 2020). Overall, different breeds respond to limited drinking water availability in different ways, with native breeds performing better in their area compared to exotic breeds (Chikwanha et al., 2021; Hussein et al., 2020) and more so in feedlot (Fletcher et al., 1985). For example, Damara and Blackhead Persian have been reported to have lower water requirements and comparable meat production and quality attributes compared to composite and improved breeds (Almeida et al., 2013; Cloete & Olivier, 2010; Schoeman & Visser, 1995b, 1995a). Furthermore, native sheep breeds have been acknowledged as particularly valuable for smallholder farmers globally owing to their ability to outperform improved breeds in water-scarce conditions (Mohapatra and Shinde, 2018; Suliman et al., 2021). However, there is limited information regarding differences in water requirements, nutrient utilisation, meat production and quality attributes among South African sheep breeds. This necessitates comparative studies of these breeds to explore their exact capabilities and particularities for potential utilisation in water scarce regions. The objective of the study was, therefore, to compare water requirements, nutrient utilisation, meat production and quality attributes of the South African sheep breeds.

4.3 Materials and methods

4.3.1 Ethical approval and study site

The animal experimental study was approved by Stellenbosch University Research Ethics Committee: Animal Care and Use (REC: ACU; Ref #: ACU-2020-11259) following guidelines of the South African National Standards (SANS 10386:2008) regarding the care and use of animals for experimental and scientific purposes. The study was conducted at the Welgevallen Experimental farm (33° 56′ 33″S 18° 51′ 59″E, Stellenbosch University, South Africa). A Multi-use USB temperature and relative humidity Data Logger (TempU03 model, TZONE DIGITAL TECHNOLOGY CO., LTD, Johannesburg, South Africa) was used to record ambient temperature and relative humidity of inside the sheep house over the experimental period (November 2020-January 2021). These two meteorological parameters were used to determine the temperature-humidity index (THI), a measure used to assess the potential heat stress in animals (Table 4.1). The THI was calculated according to Marai et al*.* (2007) using the follow equation:

$$THI = Tdb - \left[\left\{0.31 - 0.31\left(\frac{RH}{100}\right)\right\} \times (Tdb - 14.4)\right],$$

Tdb is the dry bulb temperature (°C), and RH is the relative humidity (%).

Table 4.1 Weekly meteorological data during the experimental period

Week	Temperature (°C)		Relative humidity (%)		Temperature-Humidity index	
	Day[a]	Night[b]	Day	Night	Day	Night
1	21.4 ± 4.42	15.4 ± 2.42	58.3 ± 15.69	73.5 ± 11.78	20.3 ± 3.50	15.2 ± 2.11
2	24.5 ± 4.39	16.2 ± 3.06	46.9 ± 10.96	69.0 ± 11.07	22.7 ± 3.35	16.0 ± 2.63
3	23.6 ± 3.65	17.7 ± 2.27	64.1 ± 14.17	82.2 ± 9.97	22.4 ± 2.83	17.4 ± 2.04
4	26.4 ± 4.05	17.1 ± 3.23	54.1 ± 12.86	77.8 ± 11.00	24.6 ± 3.11	16.8 ± 2.86
5	27.4 ± 4.54	20.3 ± 2.49	56.1 ± 14.15	76.2 ± 10.94	25.5 ± 3.42	19.8 ± 2.08
6	26.2 ± 5.39	18.1 ± 2.76	50.0 ± 15.83	70.2 ± 12.98	24.2 ± 4.02	17.6 ± 2.29

[a] Daytime measurement were taken at 06:00, 09:00, 1200 and 15:00. [b] Night time measurement were taken at 18:00, 21:00, 00:00 and 03:00. Heat stress categories: <22.2 = absence of heat stress, 22.2 to <23.3 = moderate heat stress, 23.3 to < 25.6 = severe heat stress and 25.6 and more = extreme severe heat stress (Source: Marai et al., 2007).

4.4 Animal management and experimental design

Fifty-seven wethers aged between 4 and 5 months were purchased from commercial farmers in the Western Cape Province of South Africa. Two pure indigenous (Pedi and Damara), indigenous composite (Meatmaster and Dorper) and exotic composite (Merino and Dohne Merino) sheep breeds raised in the South Africa were evaluated. Before the start of the trial, animals were kept off feed for 16 h then weighed to obtain the initial empty body weights. The average initial body weights (LW ± SD) of the animals were as follows: Pedi (21.7 ± 1.07 kg, n=8), Meatmaster (39.1 ± 0.96 kg, n=9) and ten of each of Damara (28.4 ± 0.96 kg), Dorper (30.9 ± 0.96 kg), Merino (33.6 ± 0.96 kg) and Dohne Merino (42.8 ± 0.96 kg). On arrival at the farm, the wethers were tagged, vaccinated against pulpy kidney using Multivax P Plus® (i.e. subcutaneous injection on the upper inner thigh) and treated for internal parasites with Tramizan® at 0.2 mg kg^{-1} LW. Lambs of each of the six breeds were randomly housed in individual pens (2 m × 1 m) with wooden slated floors. Each pen was equipped with a feeder and a waterer (i.e. 5 litre plastic bucket). Each animal represented an experimental unit. The study period lasted 70 days, which consisted of two trials conducted concurrently using the same animals. The first 21 days were used for the adaptation period, followed by digestibility (d 22-28) and water intake, growth and meat quality (d 29-70) trials. Six animals of each breed were randomly selected for the digestibility trial while the growth trial used all the animals within a breed. One Pedi lamb and one Meatmaster were injured during trial and excluded from the study.

4.5 Digestibility trial

4.5.1 Feed and watering regimes

Feed, water, faecal and urine samples from each animal were collected and quantified during this period for 7 days. All lambs had *ad libitum* access to a total mixed commercial pelleted sheep finisher diet provided daily at 08:00 (Table 4.2). Daily feed offered and refusals were weighed for determination of voluntary feed intake and the subsequent dry matter intake (DMI). Feed was offered at 10% extra of the previous day's consumption. Four litres of clean freshwater were provided into clean buckets twice a day at 08:30 and 16:00. Each animal had *ad libitum* access to water. Water remaining in each bucket was measured daily before the provision of clean water. Corrections for evaporative losses were made by placing four buckets containing 4 litres of water in different areas in the sheep house.

4.5.2 Faecal and urine sample collection

Faecal samples were collected directly from the rectum once daily using the faecal grab technique (~50 g; Da Costa et al., 2019) for seven consecutive days. Each day, the samples were stored at -20°C. After the collection period, samples were thawed and pooled per animal, weighed and dried at 60°C for 48 h. Dried samples were ground using a Wiley mill (Model 4, Thomas Scientific, Swedesboro, NJ, USA) fitted with a 1 mm sieve, and then stored at 4°C pending analyses. Spot urine samples were also collected from each animal at 12:00 for 7 days. The spot samples were obtained by transient apnoea, whereby the first operator, occluded the sheep's nostrils with both thumbs and the mouth with the palms for 10-35 sec until the sheep urinated in a clean, container held by second operator (Benech et al., 2015; Sadri et al., 2018). Occlusion of the nostril was maintained for that period to avoid compromising the welfare of the animals. Subsamples were filtered through glass wool and 10 mL aliquots were filtered and diluted immediately with 40 mL of a 0.036 N sulphuric acid (dos Santos et al., 2018) to avoid degradation of purine derivatives and precipitation of uric acid. A 20 mL subsample of the undiluted urine was stored at -20°C for creatinine and nitrogen analyses.

4.5.3 Chemical analysis of experimental diet, faecal and urine

Proximate parameters, dry matter (DM), ash, nitrogen (N) and ether extract (EE) contents in feed and faecal samples were determined using the (AOAC, 2002) methods: 934.01, 942.05, 968.06 and 920.39, respectively. Urinary N was determined using the preceding AOAC (2002) method. A factor of 6.25 was used to calculate the final crude protein (CP) content. Ash-free neutral detergent fibre (aNDFom) was determined using heat-stable α-amylase and sodium sulphite (Mertens et al., 2002) as modified by Raffrenato and Van Amburgh (2011). Acid detergent fibre (ADFom) and lignin (sa) were determined as described by Raffrenato and Van Amburgh (2011).

Table 4.2 Chemical composition of experimental diet

Variable	Composition (g/kg DM)
Dry matter	895.5
Ash	78.4
Crude protein	143.5
Ether extract	35.3
Starch	202.2
Metabolisable energy (MJ/ kg DM)	10.29
Non-fibrous carbohydrates (NFC)[a]	448.2
Neutral detergent fibre (aNDFom)[b]	294.6
Acid detergent lignin (ADL)[c]	68.1

[a]-Non-fibrous carbohydrates: Calculated as: 1000-(aNDFom + CP + EE + Ash).
[b]-aNDFom: neutral detergent fibre assayed with heat stable amylase.
[c]-Lignin: determined by solubilisation of cellulose with 72% sulphuric acid.

4.5.4 Creatinine concentration and urine output

The creatinine concentration (mg dL^{-1}) of each animal was obtained from the pooled 7-day subsamples. The final creatinine was quantified by the enzymatic method from an alkaline picrate reaction using a commercial creatinine colorimetric assay kit (Sarcosine Oxidase method; E-BC-K186-M, Elabscience®, Biocom Africa, Centurion, South Africa). Urine output was determined using the following equation:

$$urine\ output\ (L/d) = \frac{9.79\ (mg\ dL^{-1})\ \times\ LW^{0.75}}{creatinine\ concentration\ (mg/dL)}$$

where 9.79 mg kg^{-1} LW per day (David et al., 2015) is the creatinine constant and $LW^{0.75}$ is the metabolic body weight of the animal.

4.6 Nutrient intake and in vitro digestibility

Daily nutrient intake of each lamb was computed as the difference between nutrients in feed offered and faeces. Apparent total tract nutrient digestibility of organic matter (OM), CP, EE and aNDFom were determined indirectly using indigestible NDF (iNDF) as an internal marker to estimate the total faecal excretion (Raffrenato et al., 2018). Long-term fermentations (240-h) were conducted to reach the maximum extent of digestion for iNDF. The 240 h *in vitro* fermentations were conducted according to Goering and Van Soest (1970) method to determine the residual *in vitro* iNDF in both feed and faecal samples for each lamb (Raffrenato et al., 2018). At the end of 240 h, the feed and faecal samples were analysed for aNDFom (Mertens et al., 2002). The faecal DM and nutrient outputs, and apparent digestibility coefficients of nutrients were calculated as follows:

$$Faecal\ DM\ output\ (g\ d^{-1}) = \left\{\frac{iNDF\ intake\ (g\ d^{-1})}{faecal\ iNDF\ (\%)}\right\} \times 100$$

$$Nutrient\ output\ in\ faeces\ (g) = Faecal\ DM\ output\ (g) \times \frac{\%\ nutrient}{100}$$

$$Apparent\ digestibility\ coefficients\ of\ nutrients = \frac{nutrient\ intake\ (g) - nutrient\ in\ faeces\ (g)}{nutrient\ intake\ (g)}$$

The *iv*NDFd of ground feed and faecal samples was performed according to the method developed by Goering and Van Soest (1970). Forty millilitres of Van Soest buffer were added to 500 mg of sample in 125 mL Erlenmeyer flasks. The flasks were placed in a shaking water bath (39.5°C) under positive CO_2 pressure to ensure an anaerobic environment. Rumen fluid from two Holstein donor cannulated cows was collected at 07:30 and stored into pre-warmed insulated Thermos flask and transported to the lab within 30 mins. The cows were on pastures. At the lab, the rumen fluid was filtered through four layers of cheesecloth, glass wool and 100 µm fabric mesh prior to inoculation in the flasks. Rumen fluid inoculation into the flasks was done immediately after the resazurin (i.e. within the buffer solution) had turned clear because of its reduction by CO_2 gas.

4.6.1 Microbial nitrogen supply and nitrogen balance

Microbial protein synthesis was estimated by the determination of urinary purine derivatives (allantoin, uric acid xanthine + hypoxanthine) by the colorimetric method (Chen and Gomes, 1992). The quantitative relationship between absorption of microbial purines and excretion of purine derivatives in urine was determined using the nonlinear equation: $Y = 0.84X + (0.15 \times LW^{0.75} \times e^{-0.25X})$, where *Y* is the excretion of microbial purine derivative in urine, *X* is the absorption of microbial purine derivative, both in mM d^{-1} and $LW^{0.75}$ is the metabolic body weight (kg) of the animal. The rumen microbial N (g N d^{-1}) post-ruminally calculated as a function of the absorbed microbial purines (*X*, mM d^{-1}) using the following equation of Chen and Gomes (1992): $\text{Microbial N (g N } d^{-1}) = \frac{X \times 70}{0.83 \times 0.116 \times 1000}$, where 70 is the content of N in purines (mg N/ mM), 0.83 is the assumed coefficient of digestibility of microbial purines and 0.116 is the mean ratio of purine-N: total-N rumen microbes. The retention of N (g d^{-1}) was determined as the difference between N intake (g·d^{-1}) – [N faeces excretion (g d^{-1}) +N urine excretion (g d^{-1})]-basal endogenous N (g d^{-1}) = (0.018 + 0.35) × $LW^{0.75}$]. The basal endogenous N considered losses of endogenous tissue and dermal as 0.35 and 0.018 in metabolic weight, respectively.

4.6.2 Water balance

The average amount of water drunk from the waterer (i.e. free water intake) per day (L d^{-1}) was determined by subtracting water remaining in the waterer (i.e. water refusals) and evaporation losses from the total amount of water provided [water drunk = water provided-water refusals-evaporative water losses)]. Feed water (i.e.

water consumed through feed) was calculated as feed moisture × voluntary feed intake. Metabolic water production was estimated as of diet bromatological analysis and calculated by multiplying the intake of digestible fat (i.e. ether extract; EE), carbohydrate and crude protein (CP) based on the assumption that 1 g of each of these respective nutrients yields 1.07, 0.56 and 0.42 g of water (Al-Ramamneh et al., 2012; Schlink et al., 2010). The total carbohydrate content (CHO) of the feed and faeces was calculated using the equation: Carbohydrate = 100 – (%CP + %EE + %ash) (Sniffen et al., 1992). Total water intake (corrected for evaporative losses) per animal per day was calculated as the sum of water drunk, feed water and metabolic water (Al-Ramamneh et al., 2012), which was expressed as a percentage of body weight or metabolic body weight. Water balance (L d^{-1}) was calculated using the following formula according to Albuquerque et al. (2020): water balance = (free water + feed water + metabolic water) – (urinary water + faecal water).

4.6.3 Water intake, growth and meat quality trial

For the growth trial, water intake was determined for all the animals within a breed over the 42-day trial. The same measurements were recorded as described under water balance, except the daily water intake (DWI) was based on the water drunk and feed water (i.e. metabolic water was not included since faecal samples were not collected to determine the digestible nutrients). Weekly, animal full body weights were determined before feeding and composite samples of feed offered were collected, then stored (4°C) for chemical analysis. On day 42, animals were off feed for 16 h to determine the final empty body weights (i.e. final weight). Average daily gain (ADG) was calculated as the amount of weight gained during the trial period divided by the number of days on trial [ADG = (Final weight – Initial weight) / days on trial]. Feed conversion ratio (FCR) was calculated as a proportion of DMI to ADG. Water utilisation efficiency (i.e. water intake to weight gain ratio) was calculated as the ratio of DWI to ADG (Ahlberg et al., 2019; Schoeman and Visser, 1995a). The water to feed ratio was calculated as the proportion of total water drunk to total feed consumed during the experimental period (National Research Council, 2007).

4.6.4 Sheep slaughter procedures

At the end of the feeding trial, lambs were transported to a commercial abattoir, 70 km from the experimental site. At the abattoir, lambs were rested in the lairage for 16 h with no access to feed but had access to fresh clean water *ad libitum*. The lambs were slaughtered according to the procedure of the South African Meat Safety Act (No. 40 of 2000). Stunning was done using 200 V and 1.4 amperes for 4 seconds.

4.6.5 Carcass measurements

The carcasses were classed based on age and fatness after dressing by qualified personnel using the South African Meat Industry Company (SAMIC) classification system (SAMIC, 2006). Hot carcass weights were recorded immediately after slaughter while the cold carcass weights were estimated as 3% shrink loss of the former weights. Temperature and pH using (Crison PH25 meter, Lasec, South Africa) of the carcass were recorded 45 min and 24 h after slaughter between the 12^{th} and 13^{th} ribs on the left *longissimus thoracis et lumborum* (LTL). Dressing percentage was calculated as a proportion of the warm carcass weight to slaughter weight. Twenty-four hours post-slaughter, the left and right LTL were removed from each carcass, vacuum-packed and transported to the Department of Animal Sciences' Meat laboratory (Stellenbosch University) under cold storage conditions. The left LTL was used for meat physicochemical, fatty acids composition and volatile compounds and retail shelf-life analyses. The right LTL was vacuum packed and stored at -20°C pending sensory evaluation.

4.6.6 Income over feed costs

The income-over-feed cost (IOFC) per animal was calculated using the following formula: IOFC = Total income (TI) − Total feed costs (TFC), where TI = income generated after selling cold carcass and, TFC = cost per kg of feed × dry matter intake (Buza et al., 2014).

4.6.7 Meat sampling

The left *longissimus lumborum* (LL) was cut perpendicular to the muscle fibres into six, ~2 cm-thick slices and each randomly allocated for proximate (2), meat cooking loss and instrumental tenderness (Warner-Bratzler shear force; WBSF; 2), fatty acids (1) and volatile compounds (1) analyses. The left *longissimus thoracis* (LT) was used for shelf-life analyses (i.e. colour, antioxidant activity, lipid and protein oxidation). Before analyses, the meat was trimmed of all subcutaneous and excess fat, and connective tissues. All samples, except for fatty acids and volatile compounds were homogenised with a FOSS® water-cooled Knifetec 1095 sample mill (Tecator AB, Höganäs, Sweden) for 10 to 15s. Physicochemical and volatile compound meat samples were stored at -20°C, while the rest were stored at -80°C for chemical analyses.

4.6.8 Meat proximate composition

Proximate analysis was conducted as described earlier (moisture, ash and CP), except for total fat, which was for included moisture (method 934.01) and ash (method 942.05) contents (AOAC, 2002). The total fat was quantified based on the procedure by Lee, Trevino and Chaiyawat (1996) after extracting the meat with 2/1 chloroform/ methanol solvent. The CP was performed on defatted meat samples.

4.6.9 Cooking loss and shear force

Duplicate samples of lamb meat weighing between 60-80 g were used for the determination of cooking loss (Honikel, 1998) and instrumental tenderness using the WBSF technique (Silva et al., 2015). Weights were taken before and after cooking in plastic bags immersed in a water bath at 80°C for 60 min. Cooking loss was calculated as the percentage of the difference of weight before and after cooking (Honikel, 1998). The cooked samples chilled for 24 h at 4°C before the determination of WBSF. Six, 2 cm cuboids (1 cm × 1 cm square cross-section) cores were cut with the longer side parallel to the muscle fibres and cut perpendicular with a V-shaped, 1 mm thick Warner Bratzler cutting blade attached to an Instron 3345 Universal (Instron®, Norwood, MA, USA) equipped with a 500 N load cell. The WBSF was reported in Newton.

4.6.10 Analyses of intramuscular fatty acids composition

The Folch et al. (1957) procedure was used to extract intramuscular lipids using a 2/1 (v/v) chloroform-methanol solvent. An aliquot of 10 mg muscle lipid was then sequentially methylated using 0.5 N sodium methoxide as a base and 5% methanolic HCl as an acid, as outlined by (Cruz-Hernandez et al., 2004). In brief, 1 mL of internal standard (U-42 M form Nu-Check Prep Inc., Elysian, MN, USA) at 1 mg of c-10-heptadecenoic acid (c10-17:1) methyl ester/ mL toluene was added to the muscle lipid aliquot in a 10 mL Kimax® tube. After which, 0.3 mL of sodium methoxide was added, vortexed, and incubated in a 50°C water bath for 15 min. The mixture was cooled for 5 mins, and 1 mL of 5% methanolic HCl was added, vortexed and incubated at 80°C in a water bath for 30 min. After cooling for 7 min, 1 mL of deionised water was added, followed by 3 mL of hexane and vortexed. The mixture was centrifuged at 1000 × g for 5 min, and then approximately 100 mg of sodium sulphate was to remove excess water. All the fatty acid methyl esters (FAME) were analysed on a GC-MS system using a 175°C temperature program.

A gas chromatograph (6890N) coupled to an inert XL EI/CI Mass Selective Detector (MSD) (5975B, Agilent Technologies Inc., Palo Alto, CA) on a 100 m × 0.25 mm internal diameter × 0.2 µm film thick Restek™ Rt-2560 capillary column equipped with a CTC Analytics PAL autosampler was used for separation of the FAMEs. The mass spectrometer was operated under electron impact mode at an ionisation energy of 70 eV, scanning from 35 to 500 m/z. Helium was used as carrier gas at a flow rate of 1 mL/ min. The initial oven temperature was set at 45°C for 4 min. In the next step, the temperature was raised at an average rate of 13°C/min until 175°C was reached and maintained for 27 min. A final ramp of 4°C/ min was completed until 215°C was reached and held for 35 minutes. In total, the run time lasted 86 minutes. An identification of FAME by GC was carried out using the reference standard GLC 463 (Nu-Check Prep Inc., Elysian, MN, USA). The reference standard UC-59M (Nu-Check Prep Inc., Elysian, MN, USA), which contains all four positional isomers of conjugated linoleic acid (CLA), was used to quantify the individual CLA isomers. Fatty acid methyl esters were quantified using internal standard-based calculations and chromatographic peak areas (Vahmani et al., 2017). Only FAME representing > 1 mg/ 100 g of meat will be included in the results.

4.6.11 Analysis of raw meat volatile compounds

Two grams of lean meat were weighed into 15 mL solid-phase microextraction (SPME) headspace vials and 50 µl of anisole (internal standard) was added. The vial was sealed with a polytetrafluoroethylene (PTFE, Teflon®)/ silicone septa and steel cap. Vials were equilibrated at 70°C for 30 min using a CombiPAL SPME autosampler (CTC, Switzerland). A fibre (conditioned by heating in a gas chromatograph injection port at 270°C for 60 min) coated with a 50/30 µm thickness of divinylbenzene/ carboxen/ polydimethylsiloxane was inserted into the headspace above the sample and held for 10 min (with agitation). The fibre was consequently withdrawn into the needle by the autosampler and inserted into the injection port of an Agilent 6890 N (Agilent Technologies, Palo Alto, CA, USA) GC coupled with a mass spectrometer (MS) detector 5975B (Agilent Technologies). The SPME fibre was desorbed and held in the injection port at 250°C for 10 min. The fibre was inserted in a fibre conditioning station for 15 min between samples for cleaning to prevent cross-contamination. The injection port was operated in pulsed split less mode (300 kPa). Volatile compounds were separated using a DB-FFAP capillary column (60 m, 0.25 mm internal diameter, 0.5 µm film thickness). The oven temperature was initially held at 70°C for 1 min, increased to 142°C at 3°C per min, followed by a further increase to 240°C at 5°C per min and held at 240°C for 3 min. The total run time per sample was 48 min. Helium was also used as the carrier gas at flow rate of 1.9 mL/ min. The transfer line was maintained at 280°C. Mass spectra was obtained using a mass selective detector working in electronic impact at 70 eV, operated in full scan mode (35-450 *m*/*z*) with the ion source and quadrupole temperatures maintained at 240°C and 150°C, respectively. Compounds were identified by first comparing their mass spectra with those contained in the NIST05 (National Institute of Standards and Technology, Gaithersburg) library, and the Wiley (275) library. Volatiles were identified by the comparison of retention indices (RI) with published RI values. The approximate quantities of the volatiles were estimated by the comparison of their peak areas with that of the *n*-alkane internal standard obtained from the total ion chromatograms, and the formula of the retention index of the substance, to be tested is as follows:

$$\mathrm{RI} = 100\left[\frac{\mathrm{T}_x - T_y}{\mathrm{T}_z - T_y} + \mathrm{N}\right]$$

where RI is the retention index of the compound of interest; N is the carbon number of the alkane eluting before compound of interest; T*x* is the retention time of the compound of interest; T*y* is the retention time of the alkane eluting before compound of interest; T*z* is the retention time of alkane eluting after compound of interest (North et al., 2019).

4.6.12 Meat shelf-life analyses

Meat samples were prepared under hygienic conditions by removing the visible fat from the lumbar region 11(L_1-L_5). Three portion cuts of ~2.0 cm from this region were used for retail shelf-life display simulating retail conditions. Each cut from one experimental unit was randomly placed in each of three white polystyrene trays corresponding to three shelf life days (d 1, 3, 7) lined with a sterile stomacher bag material. The trays were wrapped using a 10 µm-thick oxygen permeable cling film with a moisture vapour transfer rate of 585 g cm^{-2} 24 h^{-1} $atmosphere^{-1}$, oxygen permeability of 25 000 cm^3 m^{-2} 24 h^{-1} $atmosphere^{-1}$ and a carbon dioxide permeability of 180 000 cm^3 m^{-2} 24 h^{-1} $atmosphere^{-1}$. All trays were displayed under continuous, cool and white fluorescent illumination for a 3-day shelf-life study at ±4°C. The trays were rotated every 24 h to minimise temperature and light intensity disparities. Samples for antioxidant activity, lipid and protein oxidation of meat cut on each sampling day (i.e. 1, 3 and 7) after taking colour measurements. Prior to analyses, samples for as described for the other meat quality parameters and stored at -80°C prior to analyses.

4.6.12.1 Colour measurements

At each shelf-life period, meat samples removed from the retail packaging and allowed to bloom for 30 min before measurements were taken. Meat colour parameters [lightness (*L**), redness (*a**) and yellowness (*b**)] were recorded (AMSA, 2012) using a Spectro-guide 45/0 gloss colorimeter (BYK-Gardner GmbH, Germany) standardised to D65/10° observer settings against white and black tiles before determination of meat colour.

4.6.12.2 Antioxidant activity analysis

Antioxidant capacity of the meat was determined using the ferric reducing ability power (FRAP) as described by Descalzo et al. (2007). Meat samples (1 g in duplicate) were homogenised in 5 ml of alkaline potassium phosphate solution (pH 7.2) using an IKA® Disperser (T18 digital ULTRA TURRAX®, IKA®, Staufen im Breisgau, Germany) set at 9000 rpm for 2 min. The homogenate was centrifuged at 4024 × *g* for 30 min at 20°C. A 20 µl supernatant was mixed with 180 µl FRAP reagent [i.e. 300 mM acetate buffer (pH 3.6), 10 mM 2,4,6-tri[2-pyridyl]-*s*-triazine solution and mL 20 mM ferric chloride solution (10/1/1)] in a 96-microplate well and shaken for 3 s before absorbance was read at 593 nm (Spectrostar Nano, BMG Labtech, Ortenberg, Germany). Antioxidant activity was quantified by comparison to a ferrous sulphate standard curve (0.1-0.8 mM) and expressed as mM ferrous sulphate equivalent per kg wet meat (mM Fe^{2+} eq. kg^{-1} meat).

4.6.12.3 Lipid oxidation analysis

The thiobarbituric acid reactive substances (TBARS) assay was used for quantifying the extent of lipid oxidation according to the procedure described by Lynch and Frei (1993) as modified by Gatellier et al et al. (2005). Duplicate, one gram meat samples were homogenised as described above but using 10 mL of 0.15 M potassium chloride at 6400 rpm for 20 s. Following the above procedure, samples were read at an absorbance of 532 nm. The TBARS were quantified by comparison to a 1,1,3,3-tetra-methoxypropane standard curve (0-20 µM) and results expressed as mg malondialdehyde per kg meat [mg Malondialdehyde (MDA) kg^{-1} meat].

4.6.12.4 Protein oxidation analysis

Protein oxidation was determined by measuring the carbonyl content of meat following the Sigma-Aldrich Protein Carbonyl Colorimetric Assay Kit (St Louis, MO, USA; Sigma-Aldrich, 2015). Carbonyl content was determined by using derivatisation with 2,4-dinitrophenyl hydrazine and was quantified by a spectrophotometric assay at 375 nm. The carbonyl content was calculated as nmol carbonyl mg^{-1} protein calculated using a molar extinction coefficient of 22 mM^{-1} cm^{-1}. All samples were analysed in duplicates.

4.6.13 Descriptive Sensory Analyses

Ethics approval to conduct the sensory study was granted by the Stellenbosch University Research Ethics Committee: Social Behavioural and Education Research committee (FESCAGRI-2020-19123). The study followed the COVID-19 regulations under adjusted alert level 2 of the Republic of South Africa [Disaster Management Act No. 27 of 2002, Amendment of Regulation issues in terms of Section 27(2)]. Prior to Descriptive Sensory Analyses (DSA), *Listeria monocytogenes*, *Escherichia coli* and *Salmonella* spp. were tested to ensure meat safety. A ten-member panel of experienced judges were trained in accordance with the American Meat Science Association (AMSA, 2015) and the consensus method described by Lawless and Heymann (2010). Frozen right LTL samples were thawed overnight (±4°C) and partitioned into LL for the training and LT for testing phases. All subcutaneous fat and connective tissue were removed from each loin. The cooking and presentation methods of the meat samples were as described in Erasmus et al. (2016). During a 4-day training phase, panellists made use of specific reference standards to formulate a list of sensory attributes (Table 4.3). The attributes tested were divided into three categories (i.e. aroma, flavour and texture).

The panellist was used over eight sessions with six loins per session randomised with respect to presentation order. Panellists were allocated individual tasting booths fitted with computers with the Compusense five® software program. Attribute intensities were rated on unstructured line scales (0-100), using the Compusense® five software program.

Table 4.3 Reference standards, definitions and scales of final aroma, flavour and textural attributes used in descriptive sensory analysis of the longissimus muscle of four South African sheep breeds.

Aroma attributes	Attribute description	Score	Reference standard used*
Lamb meat	Aroma associated with a roasted feedlot lamb meat	0 = None, 100 = Prominent	Lamb S = 60; Lamb = 70-80
Lamb fat	Aroma associated with roasted feedlot lamb fat	0 = None, 100 = Prominent	Lamb S = 30; Lamb = 40; Lamb fat = 80-90
Savoury broth aroma	Aromatics associated with salty, meaty and brothy characteristics	0 = None, 100 = Prominent	Lamb = 10-20; Lamb W/S = 40; Sav B = 70
Sweet-associated aroma	Aroma associated with the browning on the surface of cooked meat (Maillard reaction products)	0 = None, 100 = Prominent	Liver = 20; Lamb = 30; Sw-A (roasted) = 40; Lamb fat = 50
Liver-like aroma	Aromatics associated with pan-fried beef ox liver	0 = None, 100 = Prominent	Liver = 80
Metallic aroma	Aromatics associated with blood on cooked ostrich rump steak; closely related to metallic aromatic	0 = None, 100 = Prominent	Metal = 30; Liver = 30
Herbaceous	Aromatics associated with fresh herbs (i.e. rosemary/ thyme/ coriander/ sage)	0 = None, 100 = Prominent	
Rancid	Aromatics commonly associated with oxidised fat and oils; may include cardboard, painty, varnish, and fishy	0 = None, 100 = Prominent	
Barnyard/Kraal	Aromatics associated with livestock	0 = None, 100 = Prominent	Lamb fat = 10
Flavour attributes	**Attribute description**	**Score***	**Reference standard used**
Lamb meat flavour	Amount of roasted feedlot lamb meat flavour identity in the sample	0 = None, 100 = Prominent	Lamb fat = 30-40; Lamb S = 70; Lamb = 70
Lamb fat flavour	Flavour associated with roasted feedlot lamb fat	0 = None, 100 = Prominent	Lamb = 20; Lamb fat = 90
Savoury broth flavour	Flavour associated with salty, meaty and brothy characteristics	0 = None, 100 = Prominent	
Salty taste	Fundamental taste factor of which sodium chloride is typical	0 = None, 100 = Prominent	Lamb W/S = 15; Chew = 30; Lamb S = 30; TE = 40
Sweet-associated flavour	Combination of sweet taste and sweet flavour; the flavour associated with the impression of sweet	0 = None, 100 = Prominent	Lamb fat = 10; Liver = 20; Lamb = 30; SW-A (roasted) = 40
Liver-like flavour	Flavour associated with pan-fried beef ox liver	0 = None, 100 = Prominent	Liver = 80
Metallic flavour	Flavour associated with cooked Ostrich rump steak or a blood-like taste	0 = None, 100 = Prominent	Liver = 20; Metal = 50
Barnyard/Kraal	Flavour of white pepper in water-associated is with livestock	0 = None, 100 = Prominent	Lamb fat = 10
Herbaceous	Flavour associated with fresh herbs (i.e. rosemary/ thyme/ coriander/ sage)	0 = None, 100 = Prominent	
Rancid flavour	Flavours commonly associated with oxidised fat and oils; may include cardboard, painty, varnish, and fishy	0 = None, 100 = Prominent	

Texture attributes	Attribute description	Score*	Reference standard used
Sustained juiciness	The impression of juiciness after five chews using the molar teeth.	0 = Extremely dry, 100 = Extremely juicy	Liver = 20-30; Lamb S = 40; Lamb W/S = 40; Metal = 50; Lamb = 50-60
Mealiness	The disintegration of muscle fibres into very small particles during the first ten chews. (Texture associated with over-matured meat).	0 = None, 100 = Abundant	Lamb = 20; Liver = 40; TE = 70; Meal 1 = 70; Meal 2 – 90
Tenderness	Impression of tenderness after the first 5 chews using molar teeth.	0 = Extremely tough, 100 = Extremely tender	Chew = 20; Metal = 30; Lamb W/S = 40; Lamb = 80; Lamb S = 80; Liver = 90; TE = 90
Residue	Residual tissue remaining after mastication (difficult to chew through). Amount of residue left in the mouth after 15 chews using molar teeth.	0 = None, 100 = Abundant	Lamb = 10; Chew = 15; Lamb W/S = 30
Fatty mouthfeel	The fatty feeling in the mouth and gum after consuming meat.	0 = None, 100 = Abundant	Lamb fat = 50-60

Table 4.3 was adapted and modified from American Meat Science Association (2015); * Reference standard scores were developed based on Muñoz and Civille (1998). Pan fried (medium heat, setting 4-spray & cook in pan) deboned lamb loin chops (±1.5 cm thick) (Superspar, Belhar S.A) for 5-10 min on regular turning – browned edges removed = **Lamb**; Pan fried (medium heat, setting 4-spray & cook in pan) deboned lamb loin chops (±1.5 cm thick) (Superspar, Belhar, S.A) with fat for 5-10 min on regular turning – mostly fat pieces = **Lamb fat**; Pan fried (medium heat, setting 4-spray & cook in pan) deboned lamb loin chops (Superspar, Belhar S.A) (±1.5 cm thick) (pinch of salt (0.50g) sprinkled on each chop) for 5-10 min on regular turning = **Lamb S** (Lamb with salt); Pan fried (medium heat, setting 4-spray & cook in pan) deboned lamb loin chops (Superspar, Belhar S.A) (±1.5 cm thick) (without salt sprinkled on it) for 5-10 min on regular turning = **Lamb W/S** (Lamb without salt); Pan fried (medium heat, setting 4-spray & cook in pan) deboned lamb loin chops (Superspar, Belhar S.A) (±1.5 cm thick) with fat for 15 min = **SW-A** (Sweet associated); Pan fried (medium heat, setting 4-spray & cook in pan) Ostrich rump steak (Woolworths, Stellenbosch, S.A) (± 4 cm cubes) for 25 min on regular turning (brown internal meat colour) – browned edges removed = **Metal**; Pan fried (medium heat, setting 4-spray & cook in pan) Ox liver (Woolworths, Stellenbosch, S.A) for 5 min on regular turning = **Liver**; Boneless commercial chicken fillets (Checkers, Stellenbosch, S.A) roasted to 80°C internal temperature = **Meal** (mealiness) **1**; Boneless commercial chicken fillets (Checkers, Stellenbosch, S.A) roasted to 90°C internal temperature = **Meal 2**; Oven roasted, butter basted, boneless chicken fillets (Woolworths, Stellenbosch, S.A) microwaved 2 min and reheated at 100°C for 8 min = Tenderness; Salami sticks (Woolworths, Stellenbosch, S.A) (0.5 cm diameter and 12 cm long) cut into 1 cm pieces = **Chew** (toughness); 5 mL of Bovril (Checkers, Stellenbosch, S.A) dissolved in 250 mL boiling water = Savoury broth; Combination of herbs: 5 g each of rosemary, thyme, sage, parsley (Superspar, Kuilsriver, S.A) in 250 mL distilled water = **Herbaceous**; Microwaved sunflower oil (Woolworths Holdings Limited, Stellenbosch, SA) for 3 min at high = **Rancid**; 0.25% sodium chloride (Checkers, Stellenbosch, S.A) solution by weighing 0.25 g of sodium chloride to 50 mL of distilled water = **Salt.** *Score refers to a score line scale marked from 0 (low intensity) to 100 (high intensity).

4.6.14 Statistical analysis

All data were tested for normality using PROC UNIVARIATE of SAS v. 9.4. (SAS Institute Inc., Cary, NC, USA). In cases where they were deviations from normality, outliners were excluded from the final analysis. Data on nutrient intake and digestibility, nitrogen and water balances, carcass traits, income over feed costs, meat physicochemical attributes, fatty acids and volatile compounds were analysed using PROC GLM of SAS v. 9.4. (SAS Institute Inc., Cary, NC, USA) with breed and animal as fixed and random factors, respectively. Data on ADG, DMI, water intake and shelf-life parameters (i.e. meat colour, antioxidant activity, lipid and protein oxidation), were analysed using a repeated measure using PROC GLIMMIX of SAS v. 9.4. (SAS Institute Inc., Cary, NC, USA) to test the effect of breed, time (day or week) and breed × time interactions as fixed factors, animal as a random factor and day or week as a repeated measure. Initial weight was incorporated as a covariate for all the growth performance and carcass attributes data. Chi-square tests were computed to determine the association of breed and carcass fat class. Data for sensory analysis was analysed using PROC GLIMMIX of SAS v. 9.4. (SAS Institute Inc., Cary, NC, USA) with breed as main effect, and session and panellist as random effects. Tukey's test was used for multiple comparisons of treatment means when significance was detected at $P \leq 0.05$ and a tendency for treatment effect was observed when $0.05 < P \leq 0.10$.

4.7 Results and discussion

4.7.1 Chemical composition of the diet

The chemical composition of the experimental diet presented in Table 4.2 shows that the CP of was adequate to meet the protein requirements of growing lambs (National Research Council, 2007). The fat content was within the range (20-50 g kg^{-1} DM) acceptable for ruminants (Pantoja et al., 1994; Van Soest, 1994) whilst aNDFom was above the predicted minimum of 247 g kg^{-1} DM required to maintain effective fermentation and ruminal microbial protein synthesis (Cannas et al., 2004; Gallo et al., 2019).

4.7.2 Nutrient intake and digestibility of South African sheep breeds

Breed influenced intake of OM, CP, aNDFom and EE in the order of Meatmaster > Damara > Dorper ≥ Dohne Merino ≥ Merino ≥ Pedi ($P \leq 0.05$; Table 4.4). Overall, the higher nutrient intakes for Meatmaster and Damara could be because of their higher voluntary feed intake. All breeds were on a similar complete feed and differences are expected from the feed intake as the quantitative nature of total pelleted mixed diets is expected to blend thoroughly during preparation to prevent separation and selection (Beigh et al., 2017; Li et al., 2021).

Breed influenced the digestibility of aNDFom ($P \leq 0.05$). Damara and Meatmaster had higher ($P \leq 0.05$) DM digestibility compared to rest of the breeds. The aNDFom digestibility was in the following order: Dorper ≥ Merino ≥ Meatmaster ≥ Damara ≥ Dohne Merino ≥ Pedi ($P \leq 0.05$; Table 4.4). The observed greater aNDFom apparent digestibility in Meatmaster and Damara could be attributed to their retention of the more fibrous components for longer in the rumen, thereby, allowing the cellulolytic microbes to digest the fibrous components of the feed more thoroughly (Akinmoladun et al., 2019). The low aNDFom digestibility reported for Pedi can be attributed to delay in the onset of fibre digestion in the rumen of breeds that are predominantly raised extensively, due to low ruminal pH on adding grain or concentrate to the animal diet (Santra et al., 2002; Snyman, 2014). On the other hand, higher aNDFom digestibility observed in Dorper can be attributed to the adaptability of Dorper to both extensive and intensive feeding systems (Cloete et al., 2000). The lack of difference in aNDFom digestibility observed between Dorper and the Merinos further confirms that there are no differences in their ability to digest fibre as suggested earlier by de Waal (1995) and Street (2018). Although there were differences in the apparent digestibility of EE among the breeds, the variation was minor and could have little significance in overall energy production since most of the energy in ruminants is derived from fibre. No breed differences were noted for OM, and CP digestibility ($P > 0.05$; Table 4.4).

4.7.3 Microbial nitrogen supply, nitrogen and water balance

Table 4.5 presents the effect of breed on creatinine concentration, estimated urine output, purine derivatives and nitrogen balance of South African sheep breeds. Creatinine concentrations and estimated urine output were affected by breed ($P \leq 0.05$). The Meatmaster and Dohne Merino had the highest levels of creatinine concentration with Damara, Dorper and Merino having intermediate, and the Pedi had the lowest ($P \leq 0.05$). The higher concentration of creatinine reported in Meatmaster and Dohne Merino with the Pedi having the lowest is attributed to different body weights as creatinine excretion is related to LW and is proportional to muscle mass (Purnami and Prima, 2018; Santos et al., 2017). Creatinine is excreted steadily per kilogram of muscle mass of the animal within various breeds and in sheep, its average daily excretion is 10.7 mg/ kg of live weight but can range from 5-13.6 mg/ kg of live weight depending on the diet (David et al., 2015; Liu and McMeniman, 2006). The total average urinary volume observed across breeds in the study was lower than those reported in literature (Marsden et al., 2020; O'Connell et al., 2016). However, the values were within expected average (0.51-6.84 litre per sheep per day) (Marsden et al., 2020).

Uric acid was influenced by breed with the order of Dohne Merino = Damara = Dorper ≥ Meatmaster ≥ Merino > Pedi ($P \leq 0.05$). The higher uric acid excretion observed for Damara and Dohne Merino compared to Merino and Pedi breeds may be re associated with differences in the activity of uricase within the liver and extra-hepatic tissues, which leads to alteration in the concentrations of purines recycled via the salvage cycle for incorporation into tissue nucleic acids versus concentrations degraded into uric acid and allantoin and excreted in the urine (Selbie et al., 2015). However, little is known about the investigated breeds' rumen microbial population and diversity which warrants further investigation. Breed had no effect on allantoin, xanthine and hypoxanthine, total purine derivatives absorbed and excreted, microbial N supply and urinary N ($P > 0.05$). The values observed for Dorper on allantoin, total purine derivatives absorbed and excreted, microbial N supply were in the ranges reported by Mupangwa et al. (2000).

Meatmaster had the highest total N intake (feed N + microbial N) followed by Damara and with the rest of the breeds having the lowest values ($P \leq 0.05$). The increased N intake from feed reported in Meatmaster can be attributed to higher DMI because N intake in an animal is directly related to the proportion of N in the diet (Antwi et al., 2020). Although Damara had lower total N intake than Meatmaster, it had the same N balance due to lower faecal N output. This would suggest that Damara have an increased N recycling (Akinmoladun et al., 2021; Walt et al., 1999). A similar trend to total N intake was observed for faecal N ($P \leq 0.05$). The high faecal N loss in Meatmaster compared to the rest of the breeds reflects high feed consumption and faecal output by this breed. Meatmaster and Damara had higher ($P \leq 0.05$) N retention than the other breeds. Nitrogen balance indicates how animals metabolise end-products and their N excretion (Geron et al., 2015). Thus, current findings indicate that Meatmaster and Damara had high N balance due to their superiority in N utilisation (de Costa et al., 2021; Geron et al., 2015).

The finding that urinary N was similar for the Merinos is contrary to earlier findings by Nolte and Ferreira (2004) who found that Dohne Merino excreted more urinary and total N. The disparities could be due to differences in diets offered in the respective trials. Faecal, urinary and N retention reported for Damara in the current study are lower to those found for rams of the same breed fed ensiled chopped whole crop maize sealed with a standard polyethylene film (Ndleleni et al., 2020) which could probably be ascribed to addition of 0.8% of urea to the diets. The N balance values for Merino in the current study were higher than those reported Azizah et al. (2021) which could be due to the lower N intakes observed in latter study. The low levels of urinary N in all the investigated breeds shows adequate fermentable energy in the rumen, resulting in positive N retention (Tshabalala et al., 2013). A positive N balance indicates that the diet supplied enough N, therefore, the animals retained their body protein reserve (Albuquerque et al., 2020).

Water balances were highest in the Meatmaster and Dohne Merino, with Pedi having the least ($P \leq 0.05$). This respectively reflects the high and low free water intake values observed for these breeds during the digestibility trial. All breeds had positive water balances indicating that water gained was more than water lost. This could be attributed to the fact that the animals did not experience severe heat stress and had enough water during the experimental period. A stable or positive water balance is important for optimum animal production (Schlink et al., 2010). However, with ruminants, the chance of a negative water balance under farm conditions are rare as the rumen is usually used as a water reservoir to avoid such scenarios (Cain et al., 2006; Silanikove, 1994).

Table 4.4 Effect of breed on nutrient intake and *in vitro* apparent nutrient digestibility of South African sheep

Variable	Breed						SEM[1]	P value
	Damara	Dohne Merino	Dorper	Meatmaster	Merino	Pedi		
***Nutrient intake* (g d^{-1})**								
Dry matter	1831^{b}	1453^{cd}	1621^{c}	2000^{a}	1472^{cd}	1440^{d}	0.08	<0.0001
Organic matter	1661^{b}	1392^{c}	1429^{c}	1831^{a}	1318^{cd}	1248^{d}	0.03	<0.0001
Crude protein	259^{b}	217^{c}	222^{c}	285^{a}	205^{cd}	194^{d}	0.01	<0.0001
Nitrogen	41.4^{b}	34.7^{c}	35.6^{c}	45.6^{a}	32.8^{cd}	31.1^{d}	2.85	<0.0001
aNDFom	531^{b}	445^{c}	457^{c}	585^{a}	421^{cd}	399^{d}	0.02	<0.0001
Ether extract	64^{b}	53^{c}	55^{c}	70^{a}	51^{cd}	48^{d}	0.003	<0.0001
Nutrient digestibility (g kg^{-1})								
Organic matter	873	873	872	873	877	866	3.71	0.3960
Crude protein	885	886	877	873	880	874	3.71	0.0790
aNDFom	591^{b}	589^{b}	622^{a}	603^{ab}	613^{ab}	566^{bc}	12.44	0.0458
Ether extract	943^{a}	939^{ab}	940^{ab}	928^{b}	933^{ab}	937^{ab}	3.34	0.0445

[1] Standard error of means. [a-d] Least square means with different alphabetical notations in the same row are significantly different ($P \leq 0.05$).

Table 4.5 Effect of breed on purine derivatives, urinary creatinine and volume and nitrogen balance of South African sheep

Variable	Breed						P value
	Damara	Dohne Merino	Dorper	Meatmaster	Merino	Pedi	
Creatinine (mg dL^{-1})	4.382 ± 0.46^{b}	4.815 ± 0.60^{a}	4.235 ± 0.99^{b}	4.804 ± 0.25^{a}	4.156 ± 0.43^{ab}	3.549 ± 0.50^{c}	0.0077
Total volume of urine (L d^{-1})	0.93 ± 0.03^{a}	0.96 ± 0.04^{a}	0.84 ± 0.09^{b}	1.02 ± 0.10^{a}	0.82 ± 0.03^{b}	0.70 ± 0.03^{c}	<0.0001
Urinary excretion, mmol d^{-1}							
Allantoin	2.02 ± 0.66	2.20 ±1.19	2.36 ± 1.90	3.47 ± 0.57	2.57 ± 1.78	2.64 ± 1.25	0.6064
Uric acid	0.71 ± 0.26^{a}	0.74 ± 0.27^{a}	0.52 ± 0.06^{b}	0.50 ± 0.14^{b}	0.46 ± 0.21^{b}	0.30 ± 0.03^{c}	0.0047
Xanthine + Hypoxanthine	0.56 ± 0.30	0.86 ± 0.20	0.76 ± 0.28	0.66 ± 0.21	0.52 ± 0.21	1.04 ± 0.43	0.0679
Total purine derivatives excreted	3.29 ± 0.85	3.81 ± 1.49	3.64 ± 1.87	4.63 ± 0.48	3.55 ± 1.82	3.97 ± 1.46	0.7532
Total purine derivatives absorbed	2.58 ± 1.40	2.78 ± 2.97	2.87 ± 3.07	4.49 ± 0.79	2.73 ± 2.91	3.83 ± 2.17	0.7587
Microbial N supply (g N d^{-1})	1.87 ± 1.02	2.02 ± 2.16	2.09 ± 2.23	3.26 ±058	1.99 ± 2.11	2.78 ± 1.58	0.7587
Nitrogen balance (g** d^{-1}**)							
Total N[1]	43.33 ± 3.55^{b}	36.69 ± 2.17^{c}	37.36 ± 5.28^{c}	48.86 ± 1.94^{a}	34.83 ± 3.08^{c}	34.28 ± 2.47^{c}	<0.0001
Faecal N	3.96 ± 2.05^{b}	4.05 ± 0.43^{b}	4.32 ± 0.73^{b}	5.77 ± 0.40^{a}	3.91 ± 0.41^{b}	4.05 ± 0.35^{b}	0.0382
Urinary N	1.28 ± 0.39	0.97 ± 0.35	0.85 ± 0.32	0.93 ± 0.22	1.20 ± 0.55	0.81 ± 0.19	0.2727
N retention	38.11 ± 4.49^{a}	31.67 ± 1.71^{b}	32.19 ± 4.75^{b}	42.17 ± 1.76^{a}	29.72 ± 3.27^{b}	29.43 ± 2.28^{b}	<0.0001

$^{a-d}$ Least square means with different alphabetical notations in the same row are significantly different ($P \le 0.05$). [1] Total nitrogen supply = nitrogen in feed + microbial nitrogen.

Table 4.6 Effect of breed on water balance of South African sheep

Variable	Breed						SEM[1]	P value
	Damara	Dohne Merino	Dorper	Meatmaster	Merino	Pedi		
Water gained ($L\ d^{-1}$)								
Free water	4.38^{b}	4.82^{a}	4.24^{bc}	4.80^{a}	4.16^{bc}	3.55^{d}	0.24	0.0077
Feed	0.22^{a}	0.19^{b}	0.19^{b}	0.24^{a}	0.17^{b}	0.16^{b}	0.01	<0.0001
Metabolic water	0.65^{a}	0.51^{b}	0.51^{b}	0.67^{a}	0.49^{bc}	0.45^{c}	0.02	<0.0001
Total water intake	4.86^{b}	5.27^{a}	4.69^{b}	5.38^{a}	4.55^{b}	3.92^{c}	0.26	0.0034
Water lost ($L\ d^{-1}$)								
Faeces	0.68^{a}	0.53^{b}	0.47^{b}	0.67^{a}	0.48^{b}	0.53^{b}	0.03	<0.0001
Urine	0.93^{b}	0.96^{ab}	0.83^{cd}	1.00^{a}	0.86^{c}	0.76^{e}	0.03	<0.0001
Total water lost	1.60^{ab}	1.49^{bc}	1.30^{d}	1.67^{a}	1.34^{cd}	1.29^{d}	0.04	0.0201
Water balance ($L\ d^{-1}$)	3.65^{ab}	4.02^{a}	3.63^{ab}	4.05^{a}	3.48^{b}	2.89^{c}	0.24	0.02341

[1] Standard error of means. $^{a-e}$ Least square means with different alphabetical notations in the same row are significantly different ($P \leq 0.05$).

4.7.4 Feed and water intake, growth, and carcass traits of South African sheep breeds

The effects of breed on water and feed intake, growth performance and carcass traits are presented in Table 4.7. The Meatmaster had the highest DMI per kg live weight (LW), followed by the Damara ($P \leq 0.05$) while the percentage of DMI was similar between the two breeds ($P > 0.05$). The percentage DMI for both breeds was above 4% with the rest of the breeds being above 3.5% of LW, an average value set for a 30 kg growing lamb (National Research Council, 2007). Mahgoub, Lu and Early (2000) reported that when lambs are offered high-quality diet, the intake can range between 4 and 5% of LW, which agrees with the present study. Besides the quality of diet, the high DMI observed for the Meatmaster could be attributed to the faster growth rate associated with its early maturity (Pulina et al., 2013; Van der Merwe, Brand and Hoffman, 2020). Dry matter intake is positively correlated to an animal's body weight, thus, the larger the weight, the higher the DMI (Pulina et al., 2013). In this regard, the Pedi consumed less feed owing to its small body weight (Almeida, 2011; Soma et al., 2012). As far as the authors know, the current study is the first to report DMI of the Pedi under feedlot conditions. The DMI in the current study agree with literature values reported for the Dorper (Brand et al., 2017), Dohne Merino (Chikwanha et al., 2019; Van der Merwe, Brand and Hoffman, 2020) and Merino (Van der Merwe, Brand and Hoffman, 2020). When DMI was expressed on a metabolic body weight ($LW^{0.75}$) basis, a similar trend was observed, but the Dohne Merino had the least intake ($P \leq 0.05$) across breeds.

As expected, breed influenced ($P \leq 0.05$) the live body weights and ADG of sheep. Except for Dorper, Meatmaster and Dohne Merino had the highest initial live and final body weights, followed by Merino with Damara and Pedi having the least values ($P \leq 0.05$). These differences could be attributed to genotypic differences across breeds (Peters et al., 2010; Van der Merwe et al., 2019). Meatmaster, an early maturing composite breed of Damara, Ile de France, Dorper, SAMM and Van Rooy breeds was expected to have highest liveweight as it was specifically bred for adaptation, fertility, growth and carcass traits (Peters et al., 2010; Van der Merwe et al., 2019). Dohne Merino developed by interbreeding Peppin-style Merino ewes and German Mutton Merino rams, and Merino are exotic breeds, but the former is a medium maturing breed whilst the latter is a late maturing breed, which could explain the observed differences in live body weights (Brand et al., 2018; Van der Merwe et al., 2019). The observation that Damara a large-framed, fat-tailed breed had comparable live body weights to Dorper, a cross between Dorset Horn and the Blackhead Persian was expected as both are hardy breeds (Almeida, 2011; Almeida et al., 2013; Brand et al., 2018). The lowest live body weights for the Pedi are explained by its small-framed body size, which is an adaptation to local multiple environmental stresses (i.e. hydric, nutritional, thermal, and parasite-induced stresses; Booysen & Molotsi, 2021; Maqhashu et al., 2020).

Table 4.7 Effect of breed on feed and water intakes, growth performance and carcass traits of South African sheep

Variable	Breed						P value
	Damara	Dohne Merino	Dorper	Meatmaster	Merino	Pedi	
Weight measures							
Final weight (kg)	45.9 ± 0.98[b]	52.0 ± 0.98[a]	43.5 ± 0.98[b]	55.8 ± 1.06[a]	44.2 ± 0.98[b]	34.6 ± 1.10[d]	<0.0001
ADG (g)	393.4 ± 21.96[a]	241.2 ± 30.72[b]	285.3 ± 18.51[b]	398.9 ± 25.3[a]	256.0 ± 17.72[b]	284.4 ± 35.52[b]	<0.0001
Feed and water intake measures							
DMI (kg d^{-1})	1.83 ± 0.05[b]	1.45 ± 0.07[cd]	1.62 ± 0.04[c]	2.00 ± 0.05[a]	1.47 ± 0.04[cd]	1.44 ± 0.08[d]	<0.0001
DMI of % body weight (LW)	4.36 ± 0.11[a]	3.77 ± 0.16[bc]	3.99 ± 0.09[b]	4.56 ± 0.11[a]	3.71 ± 0.09[c]	3.80 ± 0.18[bc]	<0.0001
DMI (g/ kg $LW^{0.75}$)	115.3 ± 2.45[a]	85.2 ± 2.53[d]	102.1 ± 2.45[b]	113.5 ± 2.68[a]	92.3 ± 2.44[c]	103.2 ± 2.93[b]	<0.0001
Free water (L d^{-1})	4.45 ± 0.177[ab]	4.64 ± 0.177[ab]	4.41 ± 0.177[ab]	4.82 ± 0.187[a]	4.30 ± 0.177[b]	3.52 ± 0.198[c]	0.0006
Water intake from feed (L d^{-1})	0.21 ± 0.005[b]	0.18 ± 0.005[d]	0.20 ± 0.005[c]	0.25 ± 0.005[a]	0.18 ± 0.005[d]	0.17 ± 0.005[e]	<0.0001
Daily water intake (DWI; L d^{-1}) ‡	4.57 ± 0.181[b]	4.83 ± 0.181[b]	4.61 ± 0.181[b]	5.08 ± 0.191[a]	4.50 ± 0.181[b]	3.75 ± 0.202[c]	0.0006
DWI (mL/ kg $LW^{0.75}$)	290.8 ± 11.22	278.1 ± 11.42	290.10 ± 11.21	285.1 ± 12.08	278.9 ± 11.18	270.9 ± 13.11	0.8243
DWI of % body weight (LW)	10.4 ± 0.52	12.5 ± 0.73	11.2 ± 0.45	11.7 ± 0.58	11.3 ± 0.43	9.55 ± 0.85	0.4643
Feed and water efficiency							
Feed conversion ratio	4.1 ± 0.22[a]	6.2 ± 0.28[c]	5.1 ± 0.23[b]	5.2 ± 0.38[bc]	5.4 ± 0.22[b]	4.0 ± 0.43[a]	<0.0001
Water intake to weight gain ratio	10.4 ± 0.72[d]	20.6 ± 0.72[a]	14.7 ± 0.72[bc]	12.0 ± 0.76[c]	14.5 ± 0.72[bc]	11.3 ± 0.81[cd]	<0.0001
Water consumed/ total DMI	2.5 ± 0.06[c]	3.0 ± 0.06[a]	2.8 ± 0.06[b]	2.5 ± 0.06[c]	3.0 ± 0.06[a]	2.8 ± 0.07[b]	<0.0001
Carcass attributes							
Warm carcass weight (kg)	20.6 ± 0.21[c]	23.8 ± 0.27[a]	24.2 ± 0.23[a]	23.7 ± 0.36[ab]	22.4 ± 0.22[b]	20.5 ± 0.42[c]	<0.0001
Cold carcass weight (kg)	20.0 ± 0.21[c]	23.1 ± 0.27[a]	23.5 ± 0.22[a]	23.0 ± 0.36[a]	21.8 ± 0.22[b]	20.0 ± 0.41[c]	<0.0001
Dressing percentage	44.6 ± 0.45[c]	51.3 ± 0.58[a]	52.6 ± 0.78[a]	51.2 ± 0.78[ab]	48.5 ± 0.47[b]	43.5 ± 0.91[c]	<0.0001

‡ DWI is the average of free water and water intake from feed. [a-e] Least square means with different alphabetical notations in the same row are significantly different (P ≤ 0.05).

The Meatmaster and Damara had higher (P ≤ 0.05) ADG compared to the rest of the breeds. The observed higher ADG for the Meatmaster and Damara could be attributed to the higher DMI compared to the other breeds. The current ADG values for Meatmaster and Damara are 37.4% and 16.3% greater compared to those reported by Van der Merwe, Brand and Hoffman (2020) and Wilkes et al. (2012) for the respective breeds. The ADG for the Dorper was comparable to that reported by Brand et al. (2017). However, other studies (Schoeman, 2000; Brand et al., 2017; Chikwanha et al., 2019; Van der Merwe, Brand and Hoffman, 2020) reported greater ADG's (4-41%) for the Dohne Merino, Dorper and Merino. Although all animals were on the same feedlot diets, these differences could have emanated from other factors such as basal diet, concentrate to forage ratio and age of the animal.

Pedi and Damara had superior FCR (19-39%) than the Dohne Merino, Dorper, Meatmaster and Merino (P ≤ 0.05). Despite these variations, the FCR across breeds were within the expected range of 3.5-6.9 (average 4.7) for the economic viability of the sheep enterprise under feedlot conditions (Cannas et al., 2019; Lima et al., 2017). However, the disparities among breeds may be ascribed to the differences in genetics, DMI, digestion and the associated rates of passage and nutrient utilisation (Claffey et al., 2018). Different breeds have different efficiencies in nutrient digestion and/or utilisation for growth of different body tissues (Brand et al., 2017; Cannas et al., 2019; Claffey et al., 2018). In addition, heavier lambs tend to have higher maintenance requirements and thus a lower FCR (Claffey et al., 2018). Some breeds can have a higher intake, but at the same time a higher passage rate of feed and lower feed digestibility, subsequently affecting nutrient absorption and utilisation (Cannas et al., 2019).

Dohne Merino, Dorper and Meatmaster recorded the highest carcass weights while Damara and Pedi had the lowest values (P ≤ 0.05). A similar trend was also observed for the dressing percentage. Carcass weights are heavily dependent on the genotype when animals are under the same nutritional treatment (Scanlon et al., 2013). Overall, warm and cold carcass weights were consistent with differences in final live weight. Animals with higher live weight gain are more likely to have heavier carcasses than light weighted lambs, thus tend to have greater muscle deposition, and consequently high slaughter weights and heavier carcasses (Chikwanha et al., 2019). However, with dressing percentage, there are exceptions, for example, the low dressing percentage observed for the Damara, despite its relatively high final live weight could be attributed to its long legs, large horns and heavier fat tails (Almeida, 2011; Tshabalala et al., 2003). In addition, Damara was reported to have heavier skins, spleens and livers than the Dorper (Tshabalala et al., 2003). The low values in the current study agree with those of Scanlon et al. (2013) who reported lower dressing percentages for the Merino and Damara. Overall, changes in dressing percentages across breeds could be due to differences in tail, rump and/or kidney fat between the indigenous breeds and their exotic counterparts (Mohapatra and Shinde, 2018; Wilkes et al., 2012). The dressing percentage reported for all the breeds in the current study were, however, within the 44-56% values reported for feedlot lambs (Wilkes, Hynd and Pitchford, 2012; Van der Merwe, Brand and Hoffman, 2020).

Meat pH at 45 mins and 24 h were both influenced by the breed (P ≤ 0.05). Overall, the Dorper carcasses had the highest temperature at 45 mins, whilst at 24 h, all the carcasses had pH less than 6°C (Thompson, 2002). The temperature decline, in conjunction with pH are critical in determining meat quality due to their effects on muscle enzymatic rates (Kerth, 2013). Breed showed a tendency on the pH after 24 h (i.e. ultimate pH; pH_{24}) where Pedi, Dohne Merino and Merino had higher (P = 0.0677) pH_{24} than other breeds. This could be associated with the genetic make-up of the breeds. For example, the Merino bloodline is known to have high pH_{24} all conditions being equal (Hopkins et al., 2011). However, there is still a gap in this area when it comes to the Pedi as there are no studies in this regard, and this warrants further research. Apart from the breed effects some level of stress before or during slaughter (Ferguson and Warner, 2008; Gardner et al., 1999) can contribute to the high pH_{24}. Overall, these values can be classified as intermediate (i.e. 5.8-6.2), which can have detrimental effects on meat quality such as dark-cutting and tougher meat (Ponnampalam et al., 2017; Purchas, 1990).

Free water intake was influenced by breed, with the Meatmaster, Dohne Merino, Dorper and Damara having higher ($P \leq 0.05$) intake than Pedi. This was expected as there is a close environment relationship between water and body weight provided there is an unlimited supply of water (Schoeman and Visser, 1995b). The minor differences in free water intake between the studied breeds, except for Pedi could be linked to the alteration of individually housed animals in terms of performance and behaviour owing to the inactivity, which can also affect water intake (Brew et al., 2011; Golher et al., 2021). Water from the feed was highest in the Meatmaster and lowest in the Pedi with the rest of the other breeds having intermediate values ($P \leq 0.05$). This was anticipated because, the animals were fed the same diet, therefore, the differences would emanate from the DMI by the animal. An animal that has a higher voluntary feed intake, will thus have higher water intake from feed. The elevated water intake from the feed for Meatmaster resulted in it having the highest daily water intake ($P \leq 0.05$). Water utilisation by the animal not only comes from free water and feed, but also from the catabolism of nutrients (i.e. metabolic water; Beede, 2012). Studies in South Africa using the Blackhead Persian, Dorper and SA Mutton Merino reported daily water intakes of 2.2, 4.6 and 5.4 L d^{-1}, respectively (Schoeman and Visser, 1995a, 1995b). These values show a similar trend when comparing between breeds (i.e. Dorper and Pedi), which fall under the same category between the current study and the previous studies (Schoeman and Visser, 1995b, 1995a). However, the SA Mutton Merino had higher intakes than the Dohne Merino in the present study.

The lack of differences in water intake observed among the studied breeds could be attributed the presence of the rumen which acts a water reservoir. In ruminants, the rumen is a huge water reservoir with the digestive tract accounting for 15 to 35% of total animal weight (Golher et al., 2021; Silanikove, 1994, 1992). Over 80% of the animal's daily water requirements are fulfilled either through drinking with the remaining through feed and metabolic water. The value of free water is comparable to those reported by Casamassima et al. (2018) in Lacaune ewes which received *ad libitum* water for 28 days. Additionally, water intake by sheep may represent two to three times the DM intake (National Research Council, 2007). In the current study, this ratio ranged between 2.5-3.2% for all the breeds ($P \leq 0.05$). However, the water intake / total DMI (2.41-2.99) was comparable to values (2.59) reported by Hadjigeorgiou et al. (2000).

The lower water intake/kg weight gain observed for the Pedi and Damara imply an efficient usage of water for every kg of meat produced (Schoeman and Visser, 1995a, 1995b). However, Dohne Merino's high DMI could have necessitated the increased water intake to cater for the elimination of waste products and evaporative cooling to dissipate the excess heat during metabolism (Alamer, 2011; Barros de Freitas et al., 2021). These high water intake/ kg weight gain values are not peculiar as Schoeman & Visser (1995a,b) reported even greater values for the Dorper (26.9 ± 1.84) and SA Mutton Merino (31.1 ± 2.13). Overall, based on the water intake to weight gain ratio, the Damara, Pedi and Meatmaster were more water efficient compared to the other breeds, which had lower water intake efficiency but producing comparable ADG.

4.7.5 Effect of breed on carcass class of South African lamb

There was an association between breed with carcass age and fatness (Table 4.8; $\chi^2 = 37.1$; $P \leq 0.05$; Cramér's V = 0.3685). The Merino had the highest number of carcasses classed as young and lean (age class A and fatness class 2) followed by the Dohne Merino with the Dorper being the third highest. However, the Damara, Meatmaster and Pedi had greater proportions of animals being classified in the higher classes, that is, A3 to A6. The Meatmaster even had 11% of the carcasses being classed as AB2. Van der Merwe, Brand and Hoffman (2020) also observed greater rates of fat deposition in Meatmaster than Dohne Merino and Merino lambs, which concurs with the current findings. Fat is a late maturing tissue (Savell, 2017), therefore, animals which mature early will have greater deposition of fat when kept under the same environmental conditions (Brand et al., 2018; Burger et al., 2013). The current study further confirms that Dohne Merino and Merino are medium and late maturing breeds (Brand et al., 2018; Van der Merwe et al., 2019), whereas Dorper, Damara, Meatmaster and Pedi are early maturing suggesting that slaughter should be based on carcass fatness rather than age or weight (Brand et al., 2017; Van der Merwe et al., 2020a,b).

Table 4.8 Proportion of different carcass age and fatness classes of South African sheep

Breed	Carcass age and fatness class					
	A2	A3	A4	A5	A6	AB2
Damara	20	50	20	10	0	0
Dohne Merino	70	20	10	0	0	0
Dorper	40	10	20	20	0	10
Meatmaster	11	33	0	33	11	11
Merino	90	10	0	0	0	0
Pedi	0	38	25	25	13	0

4.7.6 Economic comparisons of South African sheep breeds

The income over feed costs for the different breeds are presented in Table 4.9. The Meatmaster had the highest total feed costs followed by the Damara, Dohne Merino, Dorper and Merino, which had intermediate values and Pedi the least ($P \leq 0.05$). The differences are credited to the DMI considering that the price of feed was constant across breeds. The total income (i.e. from sales of carcasses) and income over feed cost was greatest for the Dohne Merino and Meatmaster and lowest for Pedi ($P \leq 0.05$). The relatively higher total income observed for the Dohne Merino and to a lesser extent Merino could be attributed on the greater percentages of animals in the A2 class Table 4.8, which is classed as premium in South Africa (Van der Merwe et al., 2020; Van Heerden et al., 2007). Meatmaster's high income was comparable to that of Dohne Merino due to its heavier carcasses. Pedi had the least income as it had lighter carcasses most (63%) of which fell into lower premium classes A4 to A6. A similar trend for income was observed for income over feed costs and the differences are also ascribed to the breed differences in carcass weights and classes.

Table 4.9 Income over feed cost of South African lamb meat

Variable	Breed						P value
	Damara	Dohne Merino	Dorper	Meatmaster	Merino	Pedi	
Total feed costs (R)[a,#]	322 ± 7.35[b]	270 ± 7.35[c]	287 ± 7.35[c]	356 ± 7.75[a]	264 ± 7.35[c]	235 ±8.22[d]	<0.0001
Total income (R)[b]	1565 ± 57.90[c]	2105 ± 57.90[a]	1680 ± 57.90[bc]	1994 ± 61.04[ab]	1773 ± 57.90[b]	1106 ± 64.74[d]	<0.0001
IOFC (R)[c]	1243 ± 58.22[c]	1836 ± 58.22[a]	1393 ± 58.22[bc]	1638 ± 61.37[b]	1509 ± 58.22[b]	871 ± 65.09[d]	<0.0001

[a] Total feed costs = feed costs per diet × dry matter intake. [b] Total income = income based on sales of cold carcasses. [c] IOFC = Total income-Total feed costs. [#] The cost of a 1 kg of feed was R4.61.

4.7.7 Effect of breed on the meat physicochemical traits of South African lamb meat

The effect of breed on the meat quality parameters are presented in Table 4.10. Most of the meat proximate parameters were significant ($P \leq 0.05$) except for Warner-Bratzler shear force (i.e. instrumental tenderness). Moisture content was highest in the Pedi and lowest in the Merino and Dohne Merino lambs ($P \leq 0.05$). On the contrary, crude protein was lowest in the Pedi and highest in the Merino and Damara lambs ($P \leq 0.05$). The highest intramuscular fat (IMF) content was observed for the Dohne Merino with Merino, Meatmaster and Dorper having moderate values whereas Damara and Pedi had the least values ($P \leq 0.05$). These proximate composition differences, particularly for Dohne Merino could be explained by interrelationships of water, protein, and fat in muscles. Muscle water content is negatively and positively correlated with fat and protein contents, respectively (Ang et al., 1984; Wati et al., 2019). In fact, fat content reduces water holding capacity due to its hydrophobicity, which consequently decreases the relative amount of protein available for attracting and holding water (Watanabe et al., 2018; Wati et al., 2019). The moisture and protein content reported for Merino and Pedi could be partly related to their carcass weights. Lighter carcases tend to have more moisture and less protein than heavier carcasses (Kemp et al., 1976; Solomon et al., 1980). The observed IMF differences across breeds also confirms that fat deposition varies among early, medium, and late maturing sheep breeds (Van der Merwe et al., 2020b). However, the low IMF recorded for Pedi and Damara is not typical of early maturing breeds and suggests that these breeds deposit most of the fat in the tail depot as opposed to carcass depots (i.e. muscle and subcutaneous) as observed for other fat-tailed breeds (Negussie et al., 2003; Van der Merwe et al., 2020). Dohne Merino and Doper had the greatest ash contents whilst Merino had the least contents ($P \leq 0.05$) and the reason for this is not immediately clear.

Cooking loss values were highest for Dorper and Meatmaster and lowest for Dohne Merino ($P \leq 0.05$). This contradicts previous findings which did not find variation in cooking loss among diverse South African sheep breeds (Cloete, Hoffman and Cloete, 2012; Van der Merwe, Brand and Hoffman, 2020). The observed cooking loss variation across breeds could be a result of the interaction of factors like pH_{24}, proximate composition and slaughter weight (De Lima Jùnior et al., 2016; Hopkins et al., 2011; Villatoro et al., 2021), which were all different in the current study. No differences were observed for the WBSF of the lamb meat across breeds ($P > 0.05$). The WBSF values reported for the current study surpassed the 40 N threshold regarded as tender for sheep meat (Holman & Hopkins, 2021). The high WBSF values obtained in this study could be associated with pH_{24} (i.e. 5.8 to 6.2), which often produce meat regarded as less tender (Grayson et al., 2016; Ponnampalam et al., 2017). However, this could depend on the consumer as Asian consumer threshold was reported to be high at higher pH_{24} (> 6.2; Zhang et al., 2021). There is, however, no established threshold for African consumers, and that warrant investigation.

Table 4.10 Effect of breed on the physicochemical quality of South African lamb meat

Variable	Breed						P value
	Damara	Dohne Merino	Dorper	Meatmaster	Merino	Pedi	
$pH_{45\ mins}$	5.9 ± 0.07^{dc}	6.3 ± 0.07^{ab}	5.9 ± 0.07^{d}	6.2 ± 0.07^{bc}	6.4 ± 0.07^{a}	6.1 ± 0.08^{bc}	<0.001
$pH_{24\ h}$	5.7 ± 0.07	5.99 ± 0.07	5.81 ± 0.07	5.95 ± 0.07	5.98 ± 0.07	6.0 ± 0.08	0.0677
Temperature 45 mins	31.2 ± 0.28^{b}	30.4 ± 0.28^{bc}	32.4 ± 0.29^{a}	30.7 ± 0.28^{b}	29.6 ± 0.28^{c}	29.6 ± 0.32^{c}	<0.001
Temperature 24 h	3.9 ± 0.26^{ab}	4.20 ± 0.26^{a}	3.20 ± 0.26^{b}	4.38 ± 0.26^{a}	4.21 ± 0.26^{a}	3.83 ± 0.29^{ab}	<0.001
Moisture (%)	73.67 ± 0.24^{b}	72.61 ± 0.26^{cd}	73.51 ± 0.24^{b}	73.20 ± 0.24^{bc}	72.28 ± 0.25^{d}	75.34 ± 0.27^{a}	<0.0001
CP (%)	23.21 ± 0.36^{ab}	22.72 ± 0.36^{bc}	22.22 ± 0.38^{bc}	22.40 ± 0.38^{bc}	23.97 ± 0.39^{a}	21.75 ± 0.49^{c}	0.0024
IMF (%)	2.63 ± 0.31^{c}	5.80 ± 0.31^{a}	3.61 ± 0.31^{b}	3.65 ± 0.31^{b}	3.42 ± 0.31^{b}	2.62 ± 0.34^{c}	<0.0001
Ash (%)	1. 3 ± 0.04^{abc}	1.25 ± 0.04^{ab}	1.25 ± 0.04^{a}	1.15 ± 0.04^{abc}	1.12 ± 0.04^{c}	1.14 ± 0.04^{bc}	0.0002
CL (%)	37.06 ± 0.67^{bc}	36.02 ± 0.67^{c}	39.72 ± 0.69^{a}	38.29 ± 0.67^{ab}	37.30 ± 0.70^{bc}	37.12 ± 0.75^{bc}	0.0061
WBSF (N)	57.30 ± 4.36	46.40 ± 4.05	53.22 ± 4.09	49.54 ± 4.16	47.43 ± 4.15	51.80 ± 4.56	0.4803

$^{a-d}$ Least square means with different alphabetical notations in the same row are significantly different (P ≤ 0.05); CL – cooking loss; WBSF – Warner-Bratzler Shear Force; CP – crude protein; IMF – intramuscular fat.

4.7.8 Effect of breed on intramuscular fatty acids of South African lamb

Table 4.11 shows the fatty acid composition of lamb meat from six South African sheep breeds. Lauric (12:0) and stearic (18:0) acids were the only SFA influenced by breed ($P \leq 0.05$). Lauric acid was highest in the Damara and Pedi, with intermediate values for the Dorper, Meatmaster and Merino and the least reported for the Dohne Merino ($P \leq 0.05$). Stearic acid proportions were highest in Damara, Dorper, Merino and Pedi ($P \leq 0.05$) with no differences observed between the Merino, Pedi, Dohne Merino and the Meatmaster ($P > 0.05$). The observed breed differences in 18:0 could be attributed to variation in microbial activities in the rumen (Maleki et al., 2015), and enzymes involved in *de novo* metabolism of 18:0 (Sampath and Ntambi, 2005). The reason that the *de novo* FA synthesis in ruminants is limited primarily to 14, 16 and 18 carbon FA (Maleki et al., 2015) and the heritability of these FA is higher than that of long-chain FA (Saatchi et al., 2013) supports that the observed breed differences in the proportions of 18:0 could be a result of genetics.

Cis-vaccenic acid (*c*11-18:1) was the only MUFA affected by breed with following trend being observed Pedi > Dorper > Damara = Meatmaster > Dohne Merino > Merino ($P \leq 0.05$). The lower proportions of *c*11-18:1 in Dohne Merino and Merino could be partly attributed to genetics and the reduced metabolism of rumen microbes (e.g. *Fusocillus* spp.) responsible for isomerisation of some *trans* 18:1 isomer to either its adjacent positional isomers or to the isomer with the opposite geometric configuration (Kemp et al., 1984).

Breed influenced the proportions of rumenic acid (RA; *c*9,*t*11-18:2), linoleic acid (LA; 18:2 *n*-6) and arachidonic acid (AA; 20:4 *n*-6)] and total *n*-6 PUFA ($P \leq 0.05$). Overall, the proportions of RA were highest in the Meatmaster and Pedi, and lowest in the Dohne Merino, Dorper and Merino ($P \leq 0.05$). The differences observed in the RA proportions across breeds could be largely related to differences in Δ9-desaturase activity. The current study, therefore, supports breed-specific regulation of Δ9-desaturase activity hypothesis (Garnsworthy et al., 2010). The lower proportion of RA observed for Dorper lambs might have been caused by rumen bacteria that favours production of propionic acid, instead of processes that promote production of *t*11-18:1 (precursor of RA) largely through LA biohydrogenation (Mierlita et al., 2011). This is true for breeds with higher genetic growth potential for meat production, favouring propionic acid production by rumen microbes, which is specific to tissue synthesis (Mierlita et al., 2011). The proportion of RA observed in this study corresponded with the values reported for lambs by Cadavez et al. (2020) and D'Alessandro et al. (2015) and were within the recommended range 0.5-1.5% (Chikwanha et al., 2018; Jaturasitha et al., 2016). The human health benefits of RA have been documented (Chikwanha et al., 2018; den Hartigh, 2018; Vahmani et al., 2020).

Linoleic acid proportions were highest for the Meatmaster and Pedi with intermediate values for the Damara and Dohne Merino and the lowest were observed for the Dorper and Merino ($P \leq 0.05$). Dohne Merino, Merino and Pedi had the highest proportion of AA followed by Meatmaster and the least were in Damara and Dorper ($P \leq 0.05$). The Meatmaster and Pedi had higher ($P \leq 0.05$) total *n*-6 PUFA compared to the rest of the breeds. Alpha-linolenic acid (ALA; 18:3 *n*-3), docosapentaenoic acid (DPA; 20:5 *n*-3) and total *n*-3 PUFA were affected by breed ($P \leq 0.05$). The proportion of ALA was higher ($P \leq 0.05$) in the Damara and Pedi than in the rest of the breeds. The Merinos had the highest proportion of DPA followed by Dorper and Pedi with the lowest found in the Damara (P ≤ 0.05). The Dohne Merino and Pedi had similar proportions of total *n*-3 PUFA but were higher (P ≤ 0.05) in comparisons to the other breeds. The finding that Pedi meat had the highest LA, ALA and total PUFA proportions was expected given that it is a lean type of meat with less IMF. Overall, the observed differences in individual and total PUFA may reflect genetic variation across breeds. Barceló-Coblijn and Murphy (2009) suggest that different genetic control mechanisms for fatty acid chain elongation and desaturation exist, which may account also for breed-dependent control mechanisms for incorporation of long-chain PUFA. Linoleic acid and ALA proportions recorded in the current study agree with other studies (Cadavez et al., 2020; D'Alessandro et al., 2015). However, they are lower than average values reported for Bergamasca, Italian Merino and Sopravissana lamb breeds (Budimir et al., 2020). Overall, LA and ALA are the most studied PUFA precursors of odour-active compounds (Elmore et al., 2002). Several volatile compounds result from the oxidation of fatty acids components of lipids, which contributes fatty aroma in cooked meat at low concentration and rancid, painty or other unpleasant flavour at high concentration (Mottram, 1998; Song et al., 2011).

Table 4.11 Effect of breed on fatty acid profile of South African lamb meat

Variable	Breed						SEM	P value
	Damara	Dohne Merino	Dorper	Meatmaster	Merino	Pedi		
12:0	0.38^{a}	0.12^{c}	0.28^{b}	0.23^{b}	0.29^{b}	0.37^{a}	0.043	0.0006
14:0	3.75	3.81	3.63	3.58	3.82	3.65	0.117	0.6301
16:0	23.5	24.3	25.5	24.7	25.0	22.8	0.838	0.2847
17:0	1.00	1.05	1.26	1.03	0.97	1.14	0.075	0.0829
18:0	17.5^{a}	15.2^{b}	17.1^{a}	15.2^{b}	16.0^{ab}	16.7^{ab}	0.406	0.0013
∑SFA	46.2	44.8	47.8	44.7	45.8	44.7	0.878	0.1156
*c*9-16:1	1.87	1.73	1.65	1.51	1.85	1.72	0.112	0.2906
*c*9-18:1	41.3	42.2	41.3	42.6	43.1	42.0	0.774	0.5263
*c*11-18:1	0.71^{ab}	0.55^{c}	0.79^{a}	0.71^{ab}	0.49^{c}	0.84^{a}	0.090	0.0475
*t*10-18:1	2.87	2.84	2.56	3.15	2.88	2.71	0.298	0.8410
*t*11-18:1	1.37	1.55	1.15	1.59	1.33	1.35	0.144	0.3309
∑MUFA	48.1	48.9	47.5	49.6	49.7	48.6	0.835	0.4247
*c*9,*t*11-18:2	0.81^{b}	0.74^{bc}	0.61^{bc}	1.01^{a}	0.67^{bc}	0.90^{ab}	0.087	0.0272
18:2 *n*-6	2.02^{bc}	1.84^{c}	1.52^{d}	2.54^{a}	1.67^{cd}	2.25^{ab}	0.217	0.0272
20:4 *n*-6	0.70^{c}	0.84^{a}	0.69^{c}	0.76^{b}	0.82^{a}	0.85^{a}	0.044	0.0458
n-6 PUFA	2.72^{c}	2.68^{c}	2.22^{d}	3.29^{a}	2.48^{cd}	3.12^{ab}	0.218	0.0178
18:3 *n*-3	1.12^{b}	1.56^{a}	1.03^{b}	0.93^{b}	0.98^{b}	1.52^{a}	0.159	0.0228
20:5 *n*-3	0.67	0.67	0.70	0.56	0.55	0.63	0.068	0.5373
22:5 *n*-3	0.49^{c}	0.80^{a}	0.65^{b}	0.48^{c}	0.74^{a}	0.61^{b}	0.074	0.0335
n-3 PUFA	2.29^{b}	3.02^{a}	2.38^{b}	1.98^{b}	2.26^{b}	2.79^{a}	0.222	0.0260
∑PUFA	5.81^{c}	6.44^{ab}	5.21^{d}	6.29^{b}	5.41^{cd}	6.80^{a}	0.402	0.0500

$^{a-d}$ Least square means with different alphabetical notations in the same row are significantly different (P ≤ 0.05). SEM-standard error of mean.

4.7.9 Effect of breed on volatile compounds of South African raw lamb meat

The profile of volatile compounds detected in the Damara, Dorper, Dohne Merino, Meatmaster, Merino and Pedi lamb meat is shown in Table 4.12. A total of 47 volatile compounds were identified and presented according to their chemical classes: alcohols (12), aldehydes (9), acids (2); esters (21); furan (1); ketone (1) and lactone (1). The proportions of hexanoic acid and total acids were influenced by breed in the order of Dohne Merino, Merino, Meatmaster, Damara and Pedi ($P \leq 0.05$). Dohne Merino had the greatest concentrations of individual (1-pentanol, hexanol, *cis*-2-octenol, 1-octen-3-ol, 1-octanol, *trans*-2-octenol and *cis*-2-octen-1-ol) and total alcohols ($P \leq 0.05$). Regarding aldehydes, Dohne Merino, Dorper and Merino had greatest concentrations of heptanal, 5-ethyl-1-cyclopentene-1-carbaldehyde, decanal, benzaldehyde and *trans*-2-decenal in comparison to the rest of the breeds ($P \leq 0.05$). However, total aldehydes were not affected by breed ($P > 0.05$). Esters were the most representative class of volatile compounds with Dohne Merino having higher proportions for methyl valerate, methyl caproate and methyl nonanoate, whilst the Pedi had the least methyl valerate, methyl caproate, ethyl caproate, methyl caprylate, methyl nonanoate, methyl caprate, allyl-2-ethylbutyrate ($P \leq 0.05$). Ethyl laurate, methyl myristate, methyl pentadecanoate, methyl palmitate, methyl palmitelaidate, methyl palmitelaolate, methyl oleate and methyl linoleate were generally lower ($P \leq 0.05$) for the Dohne Merino compared to the rest of the breeds. The identified furan (2-pentylfuran) and ketone (acetoin) were not influenced by breed ($P > 0.05$). The 4-Methyl-5-decanol, a lactone, followed the order of Dohne Merino > Merino > Dorper > Damara ≥ Meatmaster > Pedi.

Dohne Merino had the highest concentrations of alcoholic volatile compounds. Similar breed differences in alcohols have been reported previously (Del Bianco et al., 2021; Zhang et al., 2020). 1-Octen-3-ol that was dominant in Dohne Merino is an oxidation product of LA and AA (Mariutti and Bragagnolo, 2017) of which the latter was also found in high proportions in this breed. Concentration of 1-octen-3-ol was, however, higher than the expected odour threshold of 1 ng g^{-1} (Karabagias, 2018). 1-Octen-3-ol contributes to meat flavour and has a mushroom, rust-like grassy odour even at lower concentrations (Calkins and Hodgen, 2007). In a previous study, 1-octanol was strongly associated with the rancid aroma of lamb meat (Ortuño et al., 2016). The greater proportions 1-hexanol and 1-pentanol in Dohne Merino were expected due to the high proportions of observed *n*-3 PUFA in this breed, which are more susceptible to oxidation (Domínguez et al., 2019a). Derivation of 1-hexanol (herbal-fatty odour) and 1-pentanol (pleasant- sweet or fruity odour) is from the degradation of homologous aldehydes during lipid and protein oxidation (Barbieri et al., 1992; Garcia et al., 1991) and their thresholds are 10 000 and 2 500 ng/g, respectively (Karabagias, 2018). Although alcohols have higher odour threshold and greater influence on consumer olfactory perception, their contribution to volatile flavour is weaker than aldehydes (Calkins and Hodgen, 2007).

Greater concentration of benzaldehyde observed in Dohne Merino is consistent with the higher proportions of its precursor, ALA found for the same breed (Zhang et al., 2020). Overall, breed differences in aldehyde levels in the current study could be attributed to the oxidation state, rancid aroma intensity, Strecker degradation and microbial metabolism of amino acids (Echegaray et al., 2021; Vasta et al., 2011). Breed has been reported to influence lamb muscle amino acid profiles and differences in microorganisms involved in the synthesis of aldehydes (Hernandez-Sanabria et al., 2013; Zhang et al., 2020). Differences between breeds is in accordance with previous reports (Elmore et al., 2000; Zhang et al., 2020), which related the high presence of aldehydes in the lambs with the high LA. However, the observation that aldehydes were the third most abundant volatiles in the current study contrasts with previous studies on lamb meat (Del Bianco et al., 2021; Karabagias, 2018; Zhang et al., 2020). Despite that, aldehydes have lower thresholds, and serve as intermediates in the formation of other flavour compounds and are critical in the overall flavour of lamb meat (Elmore et al., 2005; Resconi et al., 2013; Roldán et al., 2015).

The variation in individual esters may also be of genetic origin. Esters in general are generated from the esterification of alcohols and carboxylic acids in meat (Song et al., 2011). Various authors reported a lower number of esters than those found in the present study (Del Bianco et al., 2021; Ortuño et al., 2016), or did not identify any compound of this chemical family (Vasta et al., 2010; Zhang et al., 2020). Despite esters having low odour thresholds, their contribution to the aroma of lamb meat may be limited (Gravador et al., 2015; Resconi et al., 2010).

Table 4.12 Effect of breed on volatile compounds (µg/ kg) of South African raw lamb meat

Variable	Chemical compound	Retention time	Retention Index	Breed						P value
				Damara	Dohne Merino	Dorper	Meatmaster	Merino	Pedi	
Acids										
Hexanoic acid	$C_6H_{12}O_2$	25.65	2060.12	3.7 ± 0.73^{bc}	7.0 ± 0.77^{a}	4.5 ± 0.82^{bc}	4.2 ± 0.73^{bc}	5.6 ± 0.82^{bc}	3.0 ± 0.82^{c}	0.0086
Nonanoic acid	$C_9H_{18}O_2$	30.18	1576.15	1.4 ± 0.35	2.4 ± 0.42	1.3 ± 0.42	1.2 ± 0.37	1.6 ± 0.42	1.0 ± 0.39	0.2325
∑ Acids				5.1 ± 0.90^{bc}	8.9 ± 0.95^{a}	5.0 ± 0.95^{bc}	5.3 ± 0.90^{bc}	6.4 ± 0.95^{ab}	4.0 ± 1.01^{c}	0.015
Alcohols										
1-Penten-3-ol	$C_5H_{10}O$	11.18	1913.64	1.4 ± 0.28	1.5 ± 0.36	0.8 ± 0.3	0.6 ± 0.30	1.1 ± 0.36	1.0 ± 0.31	0.3425
1-Pentanol	$C_5H_{12}O$	13.81	2312.12	4.1 ± 0.73^{bc}	7.54± 0.74^{a}	4.5 ± 0.77^{bc}	3.4 ± 0.78^{c}	5.9 ± 0.83^{bc}	3.3 ± 0.71^{c}	0.0031
Hexanol	$C_6H_{14}O$	16.38	2213.79	7.0 ± 1.50^{c}	17.0 ± 1.71^{a}	7.5 ± 1.71^{c}	5.4 ± 1.50^{c}	12.7 ± 1.71^{b}	7.2 ± 1.60^{c}	<0.0001
Cis-2-Octenol	$C_8H_{16}O$	17.95	2000.83	1.7 ± 0.34^{ab}	3.2 ± 0.48^{a}	1.3 ± 0.40^{b}	1.7 ± 0.34^{ab}	2. ± 0.43^{ab}	1.4 ± 0.38^{ab}	0.049
1-Octen-3-ol	$C_8H_{16}O$	18.46	2043.33	15.1 ± 2.76^{bc}	28.4 ± 2.91^{a}	16.7 ± 2.9^{bc}	13.2 ± 2.76^{c}	21.7 ± 3.30^{b}	13.9 ± 3.09^{c}	0.0041
Heptanol	$C_7H_{16}O$	18.53	1863.64	3.8 ± 0.71	6.7 ± 0.86	4.5 ± 0.75	3.8 ± 0.67	5.7 ± 0.86	3.8 ± 0.748	0.051
1-Octanol	$C_8H_{18}O$	20.48	2211.67	3.2 ± 0.47^{b}	5.4 ± 0.53^{a}	2.6 ± 0.57^{b}	2.9 ± 0.47^{b}	4.1 ± 0.57^{ab}	2.6 ± 0.53^{b}	0.0029
Trans-2-Octenol	$C_8H_{16}O$	21.52	2298.33	4.6 ± 0.85^{ab}	8.3 ± 0.95^{a}	4.0 ± 1.95^{b}	3.6 ± 0.85^{b}	4.7 ± 1.09^{ab}	3.5 ± 0.95^{b}	0.0082
Cis-2-Octen-1-ol	$C_8H_{16}O$	21.51	2297.5	4.2 ± 0.71^{ab}	7.4 ± 0.85^{a}	2.8 ± 0.85^{b}	3.4 ± 0.71^{b}	4.6 ± 0.91^{ab}	3.3 ± 0.79^{b}	0.0053
1-Nonanol	$C_9H_{20}O$	22.26	1348.56	1.4 ± 0.26	2.1 ± 0.30	1.5 ± 0.27	1.2 ± 0.21	2.1 ± 0.27	1.5 ± 0.26	0.1543
1-Pentanedecanol	$C_{15}H_{32}O$	27.96	1555.43	2.9 ± 0.39	3.4 ± 0.44	3.3 ± 0.44	2.3 ± 0.39	3.3 ± 0.47	2.6 ± 0.44	0.3491
Pentadecanol	$C_{15}H_{32}O$	27.96	1555.43	2.8 ± 0.39	3.4 ± 0.44	3.2 ± 0.44	2.3 ± 0.39	3.3 ± 0.47	2.6 ± 0.44	0.3891
∑ Alcohol				50.9 ± 7.21^{b}	79.9 ± 7.60^{a}	46.8 ± 7.60^{b}	43.0± 7.21^{b}	54.2 ± 7.60^{b}	46.5 ± 8.06^{b}	0.0146
Aldehydes										
Hexanal	$C_6H_{12}O$	7.34	1174.71	3.5 ± 1.02^{b}	8.00 ± 1.44^{a}	4.4 ± 1.14^{b}	3.4 ± 1.02^{b}	7.3 ± 1.14^{a}	3.3 ± 1.14^{b}	0.019
Heptanal	$C_7H_{14}O$	11.56	1335.61	2.2 ± 0.56^{ab}	2.0 ± 0.80^{ab}	3.3 ± 0.63^{ab}	0.9 ± 0.59^{c}	4.1 ± 0.73^{a}	1.4 ± 0.63^{bc}	0.0155
Octanal	$C_8H_{16}O$	14.71	1730.83	3.1 ± 0.60	5.2 ± 0.84	3.3 ± 0.67	2.5 ± 0.63	3.6 ± 0.67	2.6 ± 0.67	0.1647
Cis-Hept-2-enal	$C_7 H_{12}O$	15.58	1640.15	1.6 ± 0.38^{b}	3.5 ± 0.49^{a}	1.5 ± 0.43^{b}	1.6 ± 0.38^{b}	2.2 ± 0.46^{ab}	1.3 ± 0.43^{b}	0.019
Nonanal	$C_9H_{18}O$	17.23	1204.02	4.01 ± 0.95	7.5 ± 1.14	4.4 ± 1.06	4.0 ± 1.0	4.4 ± 1.1	3.1 ± 1.06	0.1121
5-Ethyl-1-cyclopentene-1-caraldehyde	$C_8H_{12}O$	17.56	1968.33	1.0 ± 0.24^{ab}	2.1 ± 0.29^{a}	1.1± 0.26^{ab}	0.7 ± 0.24^{b}	1.5 ± 0.29^{ab}	1.0 ± 0.27^{ab}	0.0199
Decanal	$C_{10}H_{20}O$	19.38	1151.03	2.3 ± 0.22^{b}	3.3 ± 0.22^{a}	2.5 ± 0.22^{ab}	2.5 ± 0.22^{ab}	2.9 ± 0.24^{ab}	2.5 ± 0.23^{ab}	0.032
Benzaldehyde	C_7H_6O	19.86	1964.39	5.2 ± 0.77^{b}	8.8 ± 0.92^{a}	6.6 ± 0.81^{ab}	3.9 ± 0.77^{b}	7.1 ± 0.99^{ab}	3.2 ± 0.86^{b}	0.0004
Trans-2-decenal	$C_{10}H_{18}O$	21.97	1192.08	1.2 ± 0.2445^{b}	2.5 ± 0.26^{a}	1.5 ± 0.26^{ab}	1.4 ± 0.25^{b}	2.1 ± 0.29^{ab}	1.1 ± 0.27^{b}	0.0021
∑ Aldehydes				68.2 ± 9.80	68.1 ± 10.33	53.6 ± 10.3	43.9 ± 9.80	49.7 ± 10.33	44.7 ± 10.96	0.3347
Esters										
Methyl valerate	$C_6H_{12}O_2$	7.59	1203.45	4.2 ± 0.38^{bc}	6.8 ± 0.41^{a}	4.9 ± 0.41^{bc}	3.7 ± 0.41^{c}	5.6 ± 0.46^{ab}	3.2 ± 0.43^{c}	<0.0001
Methyl caproate	$C_7H_{14}O_2$	11.7	1346.21	14.6 ± 4.55^{bc}	29.2 ± 4.80^{a}	24.9 ± 4.80^{a}	12.3 ± 4.55^{bc}	19.0 ± 4.80^{ab}	8.1 ± 5.09^{c}	0.031
Ethyl caproate	$C_8H_{16}O_2$	11.71	1480.83	16.9 ± 1.98^{bc}	27.5 ± 2.37^{a}	16.5 ± 2.22^{bc}	18.3 ± 1.98^{b}	23.0 ± 2.22^{ab}	13.6 ± 2.22^{c}	0.0011
Vinyl caproate	$C_8H_{14}O_2$	15.64	1817.5	4.5 ± 1.03^{b}	8.6 ± 1.33^{a}	4.8 ± 1.23^{b}	3.8 ± 1.08^{b}	7.0 ± 1.23^{a}	3.4 ± 1.23^{b}	0.0408
Methyl caprylate	$C_9H_{18}O_2$	15.75	1201.72	19.2 ± 2.94^{b}	19.8 ± 3.10^{b}	16.2 ± 3.10^{b}	23.1 ± 2.94^{b}	30.3 ± 3.10^{a}	14.8 ± 3.3^{b}	0.0143
Methyl nonanoate	$C_{10}H_{20}O_2$	17.15	1149.13	11.9 ± 1.18^{ab}	16.2 ± 1.24^{a}	12.4 ± 1.24^{ab}	12.1 ± 1.24^{ab}	14.7 ± 1.41^{a}	8.3± 1.32^{bc}	0.0023

Methyl caprate	$C_{11}H_{22}O_2$	19.26	1217.04	23.7 ± 1.85^{b}	21.8 ± 1.85^{b}	21.4 ± 1.85^{b}	28.8 ± 1.85^{a}	28.6 ± 2.10^{a}	19.4 ± 1.97^{b}	0.0035
Allyl-2-Ethylbutyrate	$C_9H_{16}O_2$	21.17	2329.17	4.4 ± 0.80^{b}	7.1 ± 0.90^{a}	4.2 ± 0.90^{b}	2.9 ± 0.80^{bc}	4.8 ± 1.04^{b}	2.8 ± 0.90^{bc}	0.0168
Ethyl laurate	$C_{14}H_{28}O_2$	21.89	1503.07	11.3 ± 0.57^{a}	8.5 ± 0.54^{b}	9.7 ± 0.54^{ab}	10.8 ± 0.57^{ab}	10.9 ± 0.61^{ab}	11.2 ± 0.57^{a}	0.0048
1-Butyl butyrate	$C_8H_{16}O_2$	24.6	2640	2.1 ± 0.27	3.1 ± 0.29	2.5 ± 0.29	2.5 ± 0.27	2.65 ± 0.31	2.5 ± 0.29	0.3143
Heptyl butyrate	$C_{11}H_{22}O_2$	25.62	1286.85	1.7 ± 0.33	2.6 ± 0.33	2.5 ± 0.33	2.0 ± 0.35	2.4 ± 0.37	2.1 ± 0.37	0.3344
Methyl myristate	$C_{15}H_{30}O_2$	25.84	1551.12	16.4 ± 1.20^{a}	8.6 ± 1.20^{b}	12.8 ± 1.98^{ab}	16.3 ± 1.20^{a}	14.1 ± 1.36^{a}	14.5 ± 1.25^{a}	0.0003
Methyl myristoleate	$C_{15}H_{28}O$	27.69	1555.43	2.6 ± 0.36	3.1 ± 0.40	3.0 ± 0.40	2.1 ± 0.36	2.8 ± 0.42	2.3 ± 0.40	0.3492
Methyl pentadecanoate	$C_{16}H_{32}O_2$	27.96	1609.63	3.6 ± 0.25^{a}	2.3 ± 0.25^{b}	3.1 ± 0.25^{ab}	3.6 ± 0.25^{a}	3.0 ± 0.28^{ab}	3.6 ± 0.27^{a}	0.0024
Methyl palmitate	$C_{17}H_{34}O_2$	29.12	1691.19	20.1 ± 1.68^{a}	11.5 ± 1.68^{b}	16.5 ± 1.68^{ab}	21.6 ± 1.59^{a}	16.4 ± 1.90^{ab}	19.9 ± 1.78^{a}	0.0013
Methyl palmitelaidate	$C_{17}H_{32}O_2$	30.49	1696.51	6.0 ± 0.49^{a}	3.2 ± 0.49^{b}	4.7 ± 0.49^{ab}	6.5 ± 0.46^{a}	4.8 ± 0.55^{ab}	5.7 ± 0.51^{a}	0.0002
Methyl palmitelaolate	$C_{17}H_{32}O_2$	30.84	1696.51	4.8 ± 0.37^{a}	2.4 ± 0.37^{b}	3.7 ± 0.37^{ab}	4.9 ± 0.37^{a}	3.9 ± 0.42^{ab}	4.5 ± 0.39^{a}	0.0002
Methyl-9-heptadecanoate	$C_{18}H_{36}O_2$	30.84	1767.38	1.8 ± 0.23	1.3 ± 0.24	1.5 ± 0.24	1.9 ± 0.23	2.2 ± 0.24	1.6 ± 0.25	0.1786
Methyl oleate	$C_{19}H_{36}O_2$	32.1	1833.01	8.5 ± 0.72^{a}	4.2 ± 0.72^{b}	6.9 ± 0.72^{ab}	8.7 ± 0.72^{a}	6.4 ± 0.82^{ab}	8.5 ± 0.77^{a}	0.0004
Methyl linoleate	$C_{19}H_{34}O_2$	33.32	1846.94	3.5± 0.31^{a}	1.6 ± 0.31^{b}	2.4 ± 0.31^{ab}	3.3 ± 0.30^{a}	2.6 ± 0.33^{ab}	3.5 ± 0.33^{a}	0.0002
Methyl ester	$C_4H_8O_3$	33.89	1547.90	11.8 ± 1.86	17.6 ± 2.08	15.2 ± 1.96	11.8 ± 1.96	16.8 ± 2.2	11.1 ± 2.08	0.108
∑ Esters				182.1 ± 10.38	194.3 ± 10.94	185.7 ± 10.94	188.8 ± 10.38	186.2 ± 10.9	163.7 ± 11.61	0.519
Ketones										
Acetoin	$C_4H_8O_2$	14.73	1302.04	44.3 ± 8.56	37.2 ± 9.03	26.8 ± 9.03	23.4 ± 8.56	21.8 ± 9.03	25.5 ± 9.57	0.4046
Furan										
2-Pentylfuran	$C_9H_{14}O$	13.05	1083.91	2.9 ±1.52	5.2 ± 2.04	7.0 ± 1.62	2.7 ± 1.45	3.7 ± 1.62	4.8 ± 1.62	0.4055
Lactones										
4-Methyl-5-decanol	$C_{11}H_{24}O$	22.07	1230.493	4.5 ± 0.81^{b}	8.3± 0.86^{a}	5.0 ± 0.86^{ab}	4.5 ± 0.77^{b}	5.8 ± 1.00^{ab}	3.5 ± 0.86^{b}	0.007

$^{a-c}$ Least square means with different alphabetical notations in the same row are significantly different (P ≤ 0.05).

4.7.10 Effect of breed on antioxidant shelf-life of South African lamb meat

Breed × day interaction influenced antioxidant activity ($P \leq 0.05$; Table 4.13). Overall, antioxidant activity declined over time with Damara and Merino having higher values on day 7 while Dohne Merino had the lowest values ($P \leq 0.05$). These findings could suggest that Damara and Merino breeds may have elevated basal levels of intrinsic redox biomarkers among them glutathione peroxidase, superoxide dismutase and catalase, which protects the cells from oxidative damage by reactive oxygen species (Bekhit et al., 2013; Skaperda et al., 2021) compared to Dohne Merino. The loss of homeostasis post-mortem could have led to the breakdown of the endogenous antioxidant defences (Carvalho et al., 2019), hence the decline in the antioxidant activity over time (Carvalho et al., 2019; Domínguez et al., 2019b).

Table 4.13 Effect of breed, day and breed × day interaction of antioxidant activity and colour of South African lamb meat

Day	Breed						P value		
	Damara	Dohne Merino	Dorper	Meatmaster	Merino	Pedi	Breed	Day	Breed × Day
Antioxidant activity (µM Fe^{2+} equivalents/ g meat)									
1	323 ± 23.169^{a}	262 ± 23.045^{bcd}	298 ± 23.013^{ab}	284 ± 24.22^{bcd}	290 ± 23.117^{abc}	249 ± 25.423^{cde}	0.3639	<0.0001	0.0090
3	252 ± 22.690^{bcde}	232 ± 23.843^{bcde}	246 ± 23.013^{bcde}	261 ± 24.753^{abcd}	280 ± 34.371^{abcd}	227 ± 29.520^{bcdef}			
7	246 ± 23.169^{bcde}	172 ± 25.509^{f}	220 ± 25.395^{def}	188 ± 29.020^{ef}	252 ± 23.117^{bcde}	224 ± 26.714^{cde}			
Lightness (L)*									
1	35.2 ± 0.618^{fghi}	33.9 ± 0.626^{i}	35.4 ± 0.618^{fghi}	34.9 ± 0.627^{ghi}	34.9 ± 0.624^{hi}	34.0 ± 0.690^{i}	0.2511	<0.0001	<0.0001
3	37.8± 0.598^{bcde}	36.6 ± 0.623^{defg}	36.1 ± 0.598^{efgh}	36.9 ± 0.600^{cdef}	38.1 ± 0.605^{bcd}	38.9 ± 0.690^{b}			
7	38.1 ± 0.622^{bc}	38.0 ± 0.639^{bcd}	38.3 ± 0.618^{bc}	37.9 ± 0.618^{cd}	38.6 ± 0.645^{bc}	40.5 ± 0.668^{a}			
Redness (a)*									
1	13.9 ± 0.412^{y}	14.0 ± 0.420^{y}	14.6 ± 0.425^{y}	13.9 ± 0.420^{y}	13.7 ± 0.415^{y}	13.9 ± 0.464^{y}	0.1068	<0.0001	0.0762
3	13.3 ± 0.407^{z}	12.2 ± 0.408^{z}	13.4 ± 0.415^{z}	13.7 ± 0.420^{z}	13.1 ± 0.407^{z}	13.5 ± 0.454^{z}			
7	12.3 ± 0.415^{z}	12.0 ± 0.424^{z}	13.0 ± 0.408^{z}	13.3 ± 0.407^{z}	12.1 ± 0.415^{z}	13.2 ± 0.464^{z}			
Yellowness (b)*									
1	9.62 ± 0.408^{e}	9.71 ± 0.408^{e}	10.9 ± 0.408^{cd}	9.68 ± 0.415^{e}	9.98 ± 0.409^{de}	9.39 ± 0.457^{e}	0.5304	<0.0001	0.0204
3	12.3 ± 0.408^{ab}	11.9 ± 0.401^{bc}	11.7 ± 0.401^{bc}	11.8 ± 0.406^{bc}	12.4 ± 0.410^{ab}	11.7 ± 0.457^{bc}			
7	12.3 ± 0.40 ^{ab}	12.5 ±0.408^{ab}	13.2 ± 0.408^{a}	12.6 ± 0.409^{ab}	12.7 ± 0.40 ^{ab}	12.8 ± 0.448^{ab}			

$^{a-i}$ Interactions with different alphabetical notations are significantly different (P ≤ 0.05). $^{y-z}$ Least square means with different alphabetical notations in the same column are significantly different (P ≤ 0.05)

4.7.11 Effect of breed on colour of South African lamb meat during shelf-life display

The effects of breed, day, and breed × day interaction of meat from sheep lambs are shown in Table 4.13. Interactive effects between breed and day were detected for lightness (*L**). Lightness increased over time with Pedi having the highest values on d 7 by followed Merino and Dohne Merino (P ≤ 0.05). The Merinos *L** values reflect their relatively high IMF content. The high *L** values reported for the Pedi meat could be related to the high moisture content reported for this breed despite that it had slow growth rates, small carcasses, high pH_{24} and low IMF, all of which are known to produce dark meat (Mapiye et al., 2013; Ponnampalam et al., 2017). Movement of water from the myofibrillar compartment into the inter-myofibrillar space and extracellular space post-mortem result in differences in the refractive indices of the cellular and extracellular space and myofibril shrinkage thereby increasing light reflection from the surface of meat making it appear lighter (Ponnampalam et al., 2017; Warriss, 2010). The *L** values across breeds are similar to those reported by Cloete et al. (2012) and Van der Merwe, Brand and Hoffman (2020) for the same breeds. The *L** values recorded in the current study are, however, slightly lower than the acceptable threshold of 44 associated with fresh meat by consumers (Holman and Hopkins, 2021; Khliji et al., 2010).

Redness (*a**) showed an interactive tendency (P = 0.076) but was affected by day, which declined over time (P ≤ 0.05). The decrease in *a** throughout the display period could be due to the increasing metmyoglobin formation because of various oxidative factors (e.g. light, exposure to oxygen), which causes the browning of the meat (Alarcon-Rojo et al., 2019; Khliji et al., 2010; Ponnampalam et al., 2020). Overall, the reported *a** values are in accordance to those reported for South African lamb breeds (Cloete, Hoffman and Cloete, 2012; Van der Merwe, Brand and Hoffman, 2020) but were below the consumer threshold (>14.5) expected for lamb meat (Holman and Hopkins, 2021). Yellowness (*b**) was influenced by the breed × day interaction resulting in values increasing over time irrespective of breeds (P ≤ 0.05). The overall increase in *b** values over time could be attributed to the formation of fluorescent Schiff bases during lipid and protein oxidation (Chelh et al., 2007). There is no set threshold for *b** in lamb meat but the results for the studied breeds are comparable to those reported in literature (Almeida et al., 2013; Van der Merwe et al., 2020).

4.7.12 Effect of breed on lipid oxidation of South African lamb meat

Day and breed × day interaction had significant effects on lipid oxidation of lamb meat (Table 4.14; P ≤ 0.05). Malondialdehyde (MDA) values increased over time (P ≤ 0.05) with Dohne Merino and Merino meat having the highest values on day 7 while Damara meat had the least values on the same day. Malondialdehyde (MDA) is one of the final products of polyunsaturated fatty acids peroxidation in cells, and therefore used a lipid peroxidation marker. In that regard, the observed breed differences in MDA values correspond with IMF and antioxidant activity values reported for the respective breeds. Lipid oxidation generally increases with IMF content and degree of unsaturation of fatty acids, and decreases with increasing antioxidant activity (Domínguez et al., 2019b). Meat lipid oxidation values were within the 1-2 mg MDA kg^{-1} meat threshold for rancidity and off-flavours acceptable to consumers (Ripoll et al., 2011) except for Dohne Merino and Merino meat on day 7.

Table 4.14 Effect of breed, day and breed × day interaction on the lipid and protein oxidation of South African lamb meat

Day	Breed						P value		
	Damara	Dohne Merino	Dorper	Meatmaster	Merino	Pedi	Breed	Day	Breed × Day
Lipid oxidation (mg MDA kg^{-1} meat)									
1	1.04 ± 0.119^{d}	1.32 ± 0.120^{bcd}	1.08 ± 0.120^{cd}	1.18 ± 0.123^{cd}	1.15 ± 0.120^{cd}	1.12 ± 0.133^{cd}	0.0646	<0.0001	<0.0001
3	1.02 ± 0.116^{d}	1.12 ± 0.116^{cd}	1.13 ± 0.117^{cd}	1.10 ± 0.121^{cd}	1.14 ± 0.118^{cd}	1.05 ± 0.131^{d}			
7	1.16 ± 0.119^{d}	2.05 ± 0.119^{a}	1.41 ± 0.123^{bc}	1.41 ± 0.123^{bc}	2.09 ± 0.120^{a}	1.30 ± 0.133^{b}			
Protein oxidation (nM carbonyl mg^{-1} protein)									
1	1.31 ± 0.411^{e}	2.02 ± 0.411^{e}	1.52 ± 0.411^{e}	1.91 ± 0.411^{e}	1.68 ± 0.411^{e}	1.47 ± 0.459^{e}	0.2917	<0.0001	0.0283
3	3.19 ± 0.411^{d}	3.83 ± 0.411^{cd}	3.67 ± 0.411^{cd}	3.79 ± 0.411^{cd}	4.28 ± 0.411^{dc}	3.68 ± 0.460^{cd}			
7	5.69 ± 0.434^{ab}	4.47 ± 0.493^{c}	6.31 ± 0.434^{a}	3.99 ± 0.461^{d}	5.87 ± 0.411^{a}	6.09 ± 0.498^{a}			

Interactions with different alphabetical notations are significantly different for each parameter (P ≤ 0.05).

4.7.13 Effect of breed on protein oxidation of South African lamb meat

Table 4.14 shows effects of breed, day and breed × day interaction on meat protein oxidation. Day and breed × day interaction showed significant differences ($P \leq 0.05$). The lowest carbonyl contents at the end of the 7-day retail display was noted in the Meatmaster with Dohne Merino having moderate values while the rest of the breeds had high values ($P \leq 0.05$) with no significant values between them ($P > 0.05$). This was not expected as these two breeds had relatively high IMF and low antioxidant activity. The levels of unsaturated fatty acids, free amino acids, high ionic strength and oxidative enzymes, which are potential precursors or catalysts for the formation of reactive oxygen species in meat (Soladoye et al., 2015) could have influenced the observed breed difference in protein oxidation but these parameters were not evaluated in this study.

4.7.14 Effect of breed on the sensory quality of South African lamb meat

The effect of breed on the aroma, flavour and textural attributes of South African lamb meat are presented in Table 4.15. All the lamb meat aroma attributes were not affected by breed ($P > 0.05$). The rest of the flavour attributes were not affected by breed except for the liver flavour. Breed influenced lamb meat liver flavour with the Meatmaster having the highest values and Damara the least ($P \leq 0.05$). The livery flavour has previously been attributed to the presence of 2-propanone (Insausti et al., 2021), which could be high in Meatmaster meat compared to the other breeds.

Tenderness, sustained juiciness and residue textural attributes of lamb meat were influenced by the breed ($P \leq 0.05$). The higher ($P \leq 0.05$) tenderness and sustained juiciness for meat from the Dohne Merino and Merino is an indication that their meat was more tender and juicier ($P \leq 0.05$) than that from the Damara and Dorper. This corresponds to the greater ($P \leq 0.05$) residues scores for the Damara and Dorper compared to Dohne Merino and Merino. It is expected that treatments with high tenderness and sustained juiciness tend to have lower residue score (Erasmus et al., 2016). The differences in tenderness and sustained juiciness could have largely emanated from the variation in the IMF and cooking loss reported for these breeds. The degree of fatness affects meat tenderness either in two ways, that is, direct effect of the fat which is softer than lean and/or indirectly through reduced muscle fibre shortening (Priolo et al., 2002). Tenderness and juiciness of the meat are negatively correlated with cooking loss (Holman and Hopkins, 2021; Hopkins et al., 2006). Overall, breed effects were more prominent for water intake, growth, and carcass attributes, but of less importance for meat shelf life and sensory quality attributes.

Table 4.15 Effect of breed on the sensory quality of South African lamb meat

Variable	Breed						SEM	P value
	Damara	Dohne Merino	Dorper	Meatmaster	Merino	Pedi		
Aroma attributes								
Lamb meat	63.9	63.4	63.5	64.5	63.8	63.8	1.266	0.7831
Lamb fat	21.9	21.3	21.7	22.3	21.9	21.7	0.520	0.0619
Metallic	3.05	3.14	3.14	3.18	2.52	2.74	0.730	0.5488
Herbaceous	9.04	9.38	8.98	9.88	9.28	8.96	0.945	0.1124
Sweet-associated	22.1	21.6	21.7	22.0	21.9	21.7	0.543	0.3201
Savoury broth	9.85	10.0	9.96	9.98	9.98	9.87	0.085	0.5107
Barnyard kraal	3.35	3.73	2.96	3.66	2.75	3.27	0.795	0.1321
Rancid	0.04	0.04	0.08	0.07	0.04	0.06	0.041	0.245
Liver	0.15	0.15	0.26	0.18	0.06	0.07	0.097	0.4798
Flavour attributes								
Lamb meat	62.4	62.4	61.07	63.0	62.7	61.7	1.270	0.2632
Lamb fat	16.4	16.1	15.5	16.8	16.5	16.4	0.874	0.0957
Metallic	2.97	2.70	2.62	2.75	2.73	3.22	0.662	0.7565
Herbaceous	6.58	7.05	6.96	6.68	6.93	6.93	6.68	0.7031
Sweet-associated	18.17	17.9	18.2	18.3	18.0	18.1	0.5155	0.6888
Savoury broth	9.96	10.0	10.2	9.90	9.84	9.96	0.1074	0.1152
Barnyard kraal	1.85	2.31	2.23	2.55	1.87	2.33	0.619	0.1722
Rancid	0.06	0.08	0.06	0.09	0.06	0.06	0.048	0.7491
Liver	0.13^{c}	0.23^{bc}	0.42^{b}	0.93^{a}	0.19^{bc}	0.24^{bc}	0.223	0.0016
Salty taste	9.60	9.74	9.78	9.64	9.71	9.66	0.280	0.9282
Texture attributes								
Tenderness	57.2^{b}	64.8^{a}	58.5^{b}	60.9^{ab}	64.2^{a}	61.3^{ab}	2.144	<0.0001
Sustained juiciness	45.9^{b}	49.1^{a}	45.7^{b}	47.6^{ab}	49.3^{a}	47.4^{b}	1.110	0.0020
Mealiness	19.4	22.1	20.7	19.8	21.9	20.5	2.945	0.2239
Residue	17.7^{a}	14.5^{c}	17.3^{a}	15.2^{b}	15.0^{b}	16.4^{ab}	1.425	0.0099
Fatty mouth coating	5.24	5.24	5.33	5.41	5.15	5.19	0.788	0.9755

$^{a-e}$ Least square means with different alphabetical notations in the same row are significantly different (P ≤ 0.05).

4.8 Conclusions

Current findings revealed important differences among South African sheep breeds. Relative to other breeds, Meatmaster and Damara had the highest DMI and ADG. In addition to Meatmaster and Damara having comparable water balance to Dohne Merino and Dorper, they had superior nutrient intake, DM digestibility, N balance and growth rates. Meatmaster and Dorper had somewhat lower income over feed costs than Dohne Merino but had similar carcass attributes and better growth rates and water utilisation efficiency. Regarding water and feed efficiencies, Pedi and Damara were superior while Dohne Merino was inferior. Dorper, Dohne Merino and Meatmaster had the heaviest slaughter and carcass weights and the highest dressing percentages whereas Damara and Pedi had the least values. The lowest and highest income over feed costs were reported for Pedi and Dohne Merino, respectively. Intramuscular fat was highest for Dohne Merino and lowest for Damara and Pedi. Pedi produced leaner meat with a more desirable fatty acid profile than the other breeds. Regarding volatile compounds, Dohne Merino generally had the greatest concentrations of acids, alcohols and aldehydes, and lowest concentrations of esters. Overall, differences in meat shelf-life and sensory attributes across breeds were minor and inconsistent. In conclusion, Meatmaster and Dorper had somewhat lower economic returns than Dohne Merino but had comparable meat production qualities and better water utilisation efficiency, which could qualify them as key feedlot breeds in water-scarce regions. Despite that Damara and Pedi had inferior carcass attributes and economic returns, they were the most water and feed efficient breeds, making them ideal water-saving breeds, especially under smallholder farming systems. Understanding the mechanisms underlying the observed variation in performance provide opportunities for selective breeding and further development of feedlot sheep breeds to cope with water scarcity. These differences could also allow producers to adopt production systems and pursue markets that corresponds with their breed choice.

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CHAPTER 5 - IMPACT OF HYDRIC STRESS ON PRODUCTION ATTRIBUTES AND MEAT QUALITY OF SHEEP BREEDS COMMONLY RAISED IN SOUTH AFRICA

5.1 Summary

Lamb production productivity and efficiency are critical factors in increasing sheep meat industry competitiveness. However, water scarcity is one factor hindering the industry's growth in South African drylands. Since sheep genetics determine meat production and quality, producers must intensify the use of local genetic resources to cope with water scarcity. Therefore, adopting breeds with low water requirements and high hydric stress tolerance in South Africa has become a high priority for the sheep industry, given the country's water challenges. Unfortunately, there is scant information on which South African sheep breeds are tolerant to water restriction under intensive (i.e. feedlot) production systems. A 42-day feedlot trial was, therefore, conducted to compare the effects of water restriction (0, 10 and 20%) and breed on the production performance and meat quality attributes of two indigenous (Pedi and Damara) and two composites (Dohne Merino and Meatmaster) South African sheep breeds. There was no interaction between water restriction × breed interaction for the investigated meat production and quality parameters. However, water restriction slightly reduced final live weight and increased meat redness without adversely influencing growth, carcass, and meat quality attributes. Overall, Meatmaster and Pedi had lower daily water intake than Dohne Merino. Meatmaster and Dohne Merino had superior carcass weights, income-over-feed-costs, lowest carcass pH, and the most tender meat relative to other breeds. Feed intake, average daily gain, and feed costs were higher in Damara than in Pedi and Meatmaster. Pedi had lighter and leaner carcasses and lower lamb meat, fat and rancid flavour scores than other breeds. It was concluded that water restriction up to 20% has no adverse effects on meat production and quality, and Meatmaster could be the ideal feedlot breed under water-scarce conditions.

Keywords: Hydric stress; South African sheep breeds; Water utilisation efficiency.

5.2 Introduction

South Africa's livestock industry contributes between 25 and 30% of the total agricultural output annually, making it the most significant agricultural subsector (Nyam et al., 2022), with sheep farming as one of the main contributors. Despite its modest share of the national economy compared to other livestock, sheep farming is a significant industry within the regional context and is strategic in developing small producers (Chikwanha et al., 2021; Cloete et al., 2014; Rust et al., 2020). One challenge of the South African sheep industry is the slow growth rate, often resulting in shortages of sheep meat in the country (Nyam et al., 2022). Although sheep farming is affected by various climatic factors, hydric stress is among the main challenges threatening production in drylands and reduces animal performance quicker and more dramatically than any other nutrient deficiency (Halimani et al., 2021; Ibidhi and Ben Salem, 2019). Managing water resources is the greatest challenge of our time, more so the combination of water scarcity and the mismanagement of water resources resulting in socioeconomic and environmental consequences (Mehdipour et al., 2022).

South Africa is the world's 30th driest country, having low but highly variable and uneven rainfall patterns, with 50% of the rain falling on just 15% of the land (Mabhaudhi et al., 2021). Water scarcity is threatening lamb meat production mainly because of its impact on fodder and water availability. However, its combination with heat stress and low fodder supplies negatively affects the physiological homeostasis of sheep, consequently compromising their health status, welfare, productive and reproductive performance (Chedid et al., 2014; Jaber et al., 2013; Sejian et al., 2012). Although there are no conclusive effects of hydric stress on meat quality, sheep deprived of water have darker meat colour because of myofibril shrinkage (Jacob et al., 2006). However, the ability of sheep to survive, reproduce and maintain homeostasis during drought depends on their genetic diversity (Sejian et al., 2019). Unfortunately, there is limited information regarding the water requirements of South African sheep breeds (Mupfiga et al., 2022; Schoeman, 2000; Schoeman and Visser, 1995). In addition, there is scant literature on the water stress tolerance of many South African sheep breeds.

For South Africa, promising low-cost water scarcity management strategies for sheep farmers include use of breeds with low water requirements and high hydric stress tolerance (Halimani et al., 2021; Mdletshe et al., 2018) under feedlot conditions. Therefore, investigating different scenarios of sheep farming under water stress conditions is essential in developing appropriate adaptation and mitigation strategies. The current study, therefore, compared feed and water intake efficiencies, growth and meat quality from South African indigenous (Damara and Pedi), indigenous composite (Meatmaster) and exotic composite (Dohne Merino) sheep breeds subjected to increasing water restriction levels under feedlot conditions.

5.3 Materials and methods

5.3.1 Ethical approval and study site

Stellenbosch University Research Ethics Committee for Animal Care and Use (REC: ACU) reviewed and approved the study (ACU-2021-23481) according to guidelines outlined in the South African National Standard (SANS 10386:2008) regarding the care and use of animals. The trial took place at Welgevallen Experimental farm (33° 56′ 33″S 18° 51′ 59″E, Stellenbosch University, South Africa) between February 2022 and April 2022.

5.3.2 Meteorological data and physiological measurements

Ambient temperature and relative humidity (Table 5.1) of the experimental house were recorded using two using portable data loggers (Multi-use USB Temp & RH Data Logger, TZONE DIGITAL TECHNOLOGY CO., LTD, Johannesburg, South Africa) secured in the middle alley (1.2 m from the ground) at two different locations within the building. The manufacturer (TZONE DIGITAL TECHNOLOGY CO., LTD, Johannesburg, South Africa) calibrated the loggers before the trial, and the data were recorded every 10 mins. In addition, heat stress conditions were monitored by the temperature-humidity index (THI; Table 5.1) (Marai et al., 2007) using the following equation:

$$THI = Tdb - \left[\left\{0.31 - 0.31\left(\frac{RH}{100}\right)\right\} \times (Tdb - 14.4)\right],$$

Tdb is the dry bulb temperature (°C), and RH is the relative humidity (%). The resultant THI values were grouped as follows: less than 22.2 (absence of heat stress), 22.2 to 23.3 (moderate heat stress), 23.3 to 25.6 (severe heat stress) and greater than 25.6 (extreme severe heat stress). Rectal temperature, respiratory rate and heart rate were measured by two trained persons once a week between 1400 and 1530 h when heat stress prediction surpassed the severe level. Rectal temperatures were measured weekly by inserting a digital thermometer (Model TCW-01, Clicks, Stellenbosch, South Africa) 3 cm into the rectum until the temperature stabilised to an accuracy of ±0.1°C. Respiration rates were determined by counting the number of respiratory flank movements for 15 secs and converted to breaths per minute. The heart rates in beats/ minute were determined using a stethoscope (Steth Deluxe D/H, KRA40, Milnerton, South Africa).

5.3.3 Blood cortisol analysis

On day 42, four animals from each treatment were randomly selected for blood cortisol analysis. Blood (4 mL) samples were collected between 1530 and 1600 from the jugular vein using 20 gauge-sterilised needles into 10-mL BD Vacutainer serum tubes containing acid-nitrate-dextrose A anticoagulant (VACULAB Plus, Lionel's Vet, Bellville, South Africa. The blood samples were stored under cold storage conditions (±4°C) and transported to a commercial laboratory for analysis.

5.3.4 Animal management and experimental design

Ninety-five lambs with an average age of 4 to 5 months, two indigenous breeds [(Damara: n = 24; 36.1 ± 2.69; (mean initial weight ± standard deviation) and (Pedi: n = 24; 22.2 ± 2.93)], one indigenous composite breed [Meatmaster: n = 24; 31.7 ± 3.35] and one exotic composite breed [Dohne Merino: n = 24; 31.8 ± 3.36] were purchased from commercial farms in the Western Cape Province of South Africa. On arrival, all the lambs were ear-tagged and drenched against internal parasites using Startect® [1% derquantel and 0.1% abamectin (*m/v*); Zoetis (Pty) Ltd., Australia] at a dose rate of 1 mL per 5 kg body weight. In addition, the lambs were vaccinated for pulpy kidney using 2 mL of Multivax P Plus. Animals were sheltered in a ventilated, well-lit house and randomly assigned to individual pens (i.e. 2 m^2) as prescribed by the South African National Standards (SANS 10386: 2008). The pen floor was constructed of slated wood to allow easy disposal of urine and faeces. Each pen was equipped with a feed trough and a secured water bucket, cleaned daily.

Lambs for each breed were randomly allocated to one of the three water restriction levels (0, control- high water intake level; 10%, medium water intake level or 20%, low water intake) in a completely randomised design with a four-by-three factorial arrangement of treatments (8 lambs per treatment). In the high water intake group (control), water was offered *ad libitum* (24 h d^{-1}) throughout the experimental period. The medium (10%) and low (20%) water intake groups were offered 90% and 80% of *ad libitum* water, respectively. Before data collection, lambs were adapted to the feed and water restriction conditions. Water intake of individual animals was measured by providing a determined volume of *ad libitum* water in a bucket at 0830 and topped up at 1530. The residual water was measured to determine the daily water intake.

The animals were fed a pelleted total mixed ration (Table 5.2) purchased from a commercial feed manufacturer. In the first 10 d, animals were adapted to the finisher diet with *ad libitum* access to water. After estimating the *ad libitum* water intake in the first 10 d, lambs were provided with water individually according to the average group requirement. Thereafter, lambs were allowed another 11 days to adapt to their respective water restriction regimes based on the following stepwise reduction: 10% water restriction group (i.e. 90% water intake) [d 11 to 12 (98%); d 13 to 14 (96%); d 15 to 16 (94%); d 17 to 18 (92%) and d 19 to 21 (90%)] and 20%

water restriction group (i.e. 80% water intake) [d 11 to 12 (96%); d 13 to 14 (92%); d 15 to 16 (88%); d 17 to 18 (84%) and d 19 to 21 (80%)]. After 21 days of the adaptation period, the 42 days of data collection commenced.

Table 5.1 Temperature, relative humidity and temperature-humidity index (mean ± SEM[1]) inside the experimental house

Week	Time	Temperature	Humidity	Temperature-humidity index
1	06:00	17.5 ± 0.64	81.6 ± 1.07	17.3 ± 0.59
	09:00	21.4 ± 0.94	74.9 ± 2.35	20.8 ± 0.85
	12:00	29.1 ± 1.73	51.4 ± 3.98	**26.6 ± 1.40**[#]
	15:00	28.0 ± 1.77	54.0 ± 3.22	**25.8 ± 1.41**
	18:00	25.9 ± 1.35	56.6 ± 2.24	***24.2 ± 1.11***[*]
	21:00	21.0 ± 0.78	68.8 ± 1.94	20.3 ± 0.70
2	06:00	16.6 ± 0.39	77.8 ± 2.12	16.5 ± 0.37
	09:00	20.9 ± 0.27	71.5 ± 2.83	20.3 ± 0.28
	12:00	31.2 ± 0.84	43.2 ± 1.74	**28.1 ± 0.70**
	15:00	32.4 ± 0.79	40.1 ± 1.48	**29.0 ± 0.63**
	18:00	29.0 ± 0.64	46.6 ± 2.70	**26.6 ± 0.55**
	21:00	21.8 ± 0.66	67.6 ± 2.17	21.1 ± 0.60
3	06:00	17.4 ± 0.67	75.9 ± 2.36	17.2 ± 0.63
	09:00	20.2 ± 0.47	74.5 ± 2.32	19.7 ± 0.45
	12:00	28.4 ± 0.98	49.4 ± 1.76	**26.2 ± 0.80**
	15:00	29.6 ± 1.12	45.5 ± 1.70	**27.0 ± 0.87**
	18:00	26.0 ± 0.87	51.2 ± 2.13	***24.1 ± 0.71***
	21:00	20.8 ± 0.59	64.6 ± 2.03	20.0 ± 0.53
4	06:00	16.0 ± 0.60	77.6 ± 2.84	15.8 ± 0.55
	09:00	17.7 ± 0.39	75.4 ± 2.71	17.4 ± 0.34
	12:00	23.5 ± 0.73	58.4 ± 3.40	22.2 ± 0.57
	15:00	23.8 ± 0.73	57.3 ± 3.80	22.4 ± 0.55
	18:00	21.8 ± 0.57	63.4 ± 3.29	20.8 ± 0.43
	21:00	18.0 ± 0.27	74.5 ± 2.18	17.7 ± 0.23
5	06:00	14.9 ± 0.67	71.9 ± 4.36	14.7 ± 0.60
	09:00	16.4 ± 0.58	69.9 ± 5.25	16.0 ± 0.48
	12:00	22.9 ± 1.49	53.7 ± 5.87	21.3 ± 1.12
	15:00	24.3 ± 1.61	49.6 ± 5.33	22.4 ± 1.20
	18:00	21.7 ± 1.17	52.6 ± 3.54	20.4 ± 0.92
	21:00	17.3 ± 0.80	65.0 ± 4.00	16.8 ± 0.68
6	06:00	15.9 ± 0.89	69.7 ± 3.22	15.6 ± 0.79
	09:00	16.3 ± 0.69	69.7 ± 2.94	16.0 ± 0.61
	12:00	25.1 ± 0.84	50.2 ± 2.35	***23.3 ± 0.69***
	15:00	25.6 ± 0.92	46.0± 2.16	***23.6 ± 0.72***
	18:00	22.3 ± 0.68	53.5 ± 2.06	21.1 ± 0.57
	21:00	18.6 ± 0.72	63.6 ± 3.21	18.0 ± 0.60

[1] SEM-standard error of means. [2] – Heat stress categories: THI < 22.2 = absence of heat stress, 22.2 to < 23.3 = moderate heat stress, 23.3 to < 25.6 = severe heat stress and 25.6 and more= extreme severe heat stress (Marai et al., 2007). [*]- Bold and italics values indicate THI between 23.3 to < 25.6. [#] = Bold values indicate THI above 25.6.

5.3.5 Animal watering, feeding management and growth performance

After the adaptation, lambs were maintained on their respective water restriction regimes (i.e. 0, 10 or 20%) for 42 days. First, the average water intake for control treatments (i.e. 0% water restriction) of each breed was calculated every morning based on the preceding day's intake. The 10 and 20% water restriction groups were then offered 90 and 80% water of *ad libitum* (unrestricted) group, respectively. However, to cater for days where the ambient temperature was predicted to be above the thermoneutral zone (TNZ) of sheep (>31°C), the quantity of water intake was monitored at 12:30, 15:30 and 18:30. If the control group's water intake increased, the amount of water was adjusted one hour after the observation. In addition, four buckets were placed within the alleys, next to the sheep pens, to adjust for evaporation. Finally, daily residual water and evaporation losses were deducted from each day's intake to determine the daily water drunk intake as follows:

$$Water\ drunk = water\ offered - (residual\ water + evaporative\ losses)$$

The water intake from feed was determined as the moisture content based on the voluntary feed intake by each animal. The daily water intake (DWI) was calculated as the summation of water drunk (i.e. water drunk) and water consumed through the feed. *Ad libitum* feed was offered daily at 1200 with the refusals from the previous 24 hours collected from each feeding trough and weighed to determine daily voluntary feed intake:

$$Voluntary\ feed\ intake\ (VFI) = feed\ offered - feed\ refusals.$$

Samples of offered feed were taken from each bag, pooled at the end of the week, and stored at -20°C for later analysis. Daily water and feed intake were computed as a percentage of the animal’s live and metabolic body weight.

On the last day of the adaptation period, lambs were kept off feed overnight (i.e. from 1600 to 0800) and individually weighed after that to obtain the fasted body weight, which was recorded as the initial weight of the study. After that, lambs were weighed weekly without restricting their feed to monitor growth performance. At the end of the trial, fasted body weights were recorded (i.e. final weight) and used to calculate average daily gain (ADG):

$$Average\ daily\ gain = \frac{final\ weight - \ initial\ weight}{days\ in\ the\ feedlot}$$

Water and feed efficiency measures were determined using water-to-gain and feed conversion ratios (Ahlberg et al., 2019). These were calculated as follows:

$Water\ to\ gain\ ratio = \frac{Daily\ water\ intake}{Average\ daily\ gain}$ and $Feed\ conversion\ ratio = \frac{Dry\ matter\ intake}{Average\ daily\ gain}$.

5.3.6 Feed chemical analysis

Chemical analysis of the feed was explained in Section 4.7.3.

5.3.7 Animal slaughter procedures

The slaughter procedure was explained 4.6.4.

5.3.8 Meat sampling and analysis

Meat sampling of lamb loins were explained in Section 4.6.7.

5.3.9 Meat proximate analyses

Meat proximate composition was explained in 4.6.8.

Table 5.2 Chemical composition of the diet fed to experimental sheep

Variable	Composition (g/kg DM)
Dry matter (DM)	90.0
Ash	62.2
Crude protein (CP)	114.5
Ether extract (EE)	36.1
Metabolisable energy (MJ/ kg DM)	12.8
Non-fibre carbohydrates (NFC)[a]	541.5
Neutral detergent fibre (aNDFom)[b]	245.6
Acid detergent fibre (ADFom)	126.9
Lignin (sa)	4.8

[a] -non-fibre carbohydrates: Calculated as 1000-(aNDFom + CP + EE + ash).

5.3.10 Cooking loss

Cooking loss measurement was explained in Section 4.6.9.

5.3.11 Colour assessment

Meat colour coordinates measurements was explained in Section 4.6.12.1.

5.3.12 Warner-Bratzler shear force

Instrumental tenderness as described in Section 4.6.9 was performed on meat samples prepared for the descriptive sensory analysis (Section 4.6.13).

5.3.13 Statistical analysis

All data were tested for normality using PROC UNIVARIATE of SAS v. 9.4 (SAS Institute Inc., Cary, NC, USA). Outliers were removed using the interquartile range (IQR) method (Kokoska and Zwillinger, 2000) in Microsoft® Excel® for Microsoft 365 MSO. The average for THI and carcass classification data were determined using the

PROC MEANS and PROC FREQ of SAS v. 9.4 (SAS Institute Inc. Cary, NC, USA). Data on water and feed intake, average daily gain, final weight, carcass traits, and meat physicochemical attributes were analysed using PROC GLIMMIX of SAS v. 9.4 (SAS Institute Inc. Cary, NC, USA) to test for the breed, water restriction and breed × water restriction interaction as the fixed effects and animal nested in the breed as a random factor. For feed and water intakes, day was incorporated as a repeated measure. The same was done with average daily gain, where week was a repeated measure and initial weight a covariate. The statistical model for sensory data included breed, water restriction and breed × water restriction interaction as fixed factors and session and panellist as random factors. The animal was used as the experimental unit for all the parameters analysed. Tukey's test was applied for least square means separation. Differences were considered significant at $P \leq 0.05$ and tendencies at $0.05 < P \leq 0.10$.

5.4 Results and discussion

5.4.1 Meteorological, temperature-humidity index and animal physiological parameters

Lambs experienced severe to extreme heat stress between 3 and 6 pm in the first three weeks of the trial when the THI was greater than a threshold of 23.3 (Marai et al., 2007). However, there was a gradual decline in heat stress levels as the growth trial progressed, except for week six, where the THI was slightly above the severe heat stress levels. The high levels of heat stress experienced in the first three weeks coincided with the end of the warm, dry summers in the Western Cape, which spans from November to March (Fauchereau et al., 2003). The end of summer signals declines in temperatures, which concurs with the reduction in the THI in the current study. These THI changes correspond with a rectal temperature decline (Fig. 5.1) observed during the experimental period.

Water restriction × breed × week interactions did not affect the rectal temperature ($P > 0.05$). However, breed × week (Fig. 5.1) and water restriction × week (Fig. 5.2) interactions influenced rectal temperature ($P \leq 0.05$). Peak rectal temperature was observed in all breeds during weeks 1, 2 and 5. However, the rectal temperature recorded was within the typical values for growing lambs (38.3-39.9°C; Marai et al., 2007; Zhang et al., 2021). Overall, at 32°C ambient temperature, sheep's rectal temperature rises above the upper THI threshold (>39.9°C; Marai et al., 2007; Zhang et al., 2021). Therefore, the increases observed in the current study are modest and expected as the animals alter their physiological mechanisms in dealing with the excessive heat load. Irrespective of breed, the animals which received *ad libitum* water intake had higher ($P \leq 0.05$) rectal temperature than those on the water restriction treatments in weeks 2, 4, 5 and 6 (Fig. 2). Breed was the only factor influencing heart rate with the Pedi averaging 115 ± 14.4 beats per minute, which was lower ($P \leq 0.05$) than the rest of the breeds. Generally, the smaller body size of indigenous tropical breeds enables them to be more adaptable to heat stress partly due to their lower feed and water requirements (Soma et al., 2012).

Breed × week interaction influenced the respiratory rate (Fig. 5.3), with Dohne Merino, generally having higher ($P \leq 0.05$) values during the growth period compared to the rest of the breeds. The Dohne Merino is an exotic composite breed with a greater thermoregulatory response for increased evaporative thermolysis to maintain core body temperature (Pulido-Rodríguez et al., 2021). These physiological mechanisms that enable animals to adjust heat tolerance are regaining interest due to climatic changes experienced in many regions.

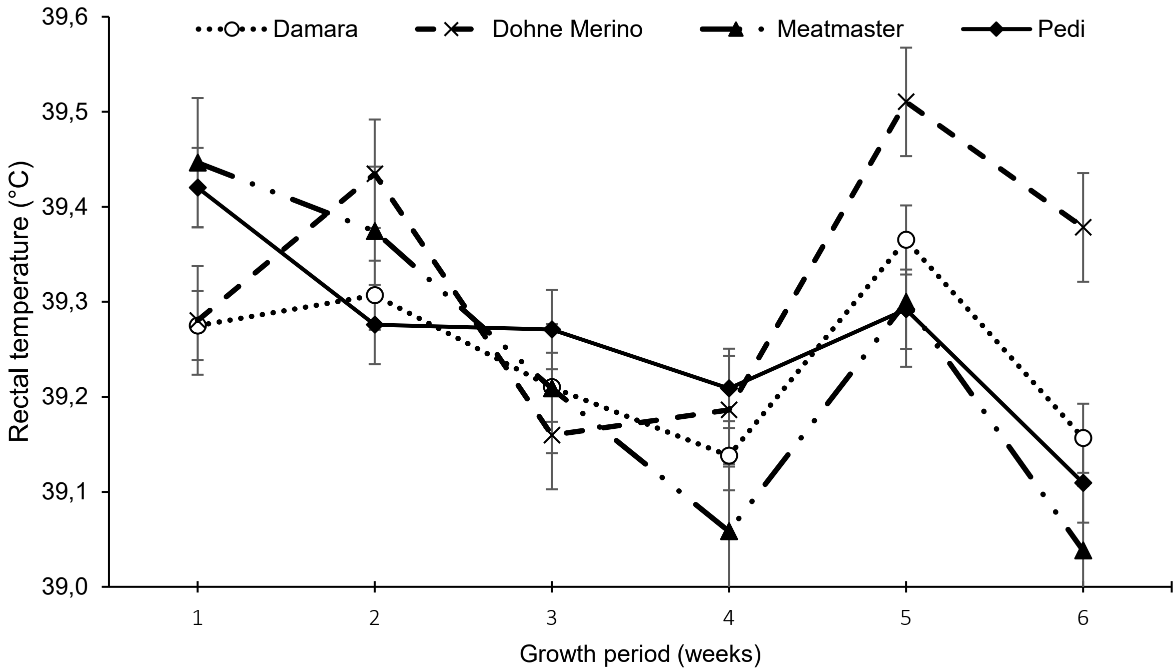

Figure 5.1 Effect of breed on the rectal temperature of selected South African sheep

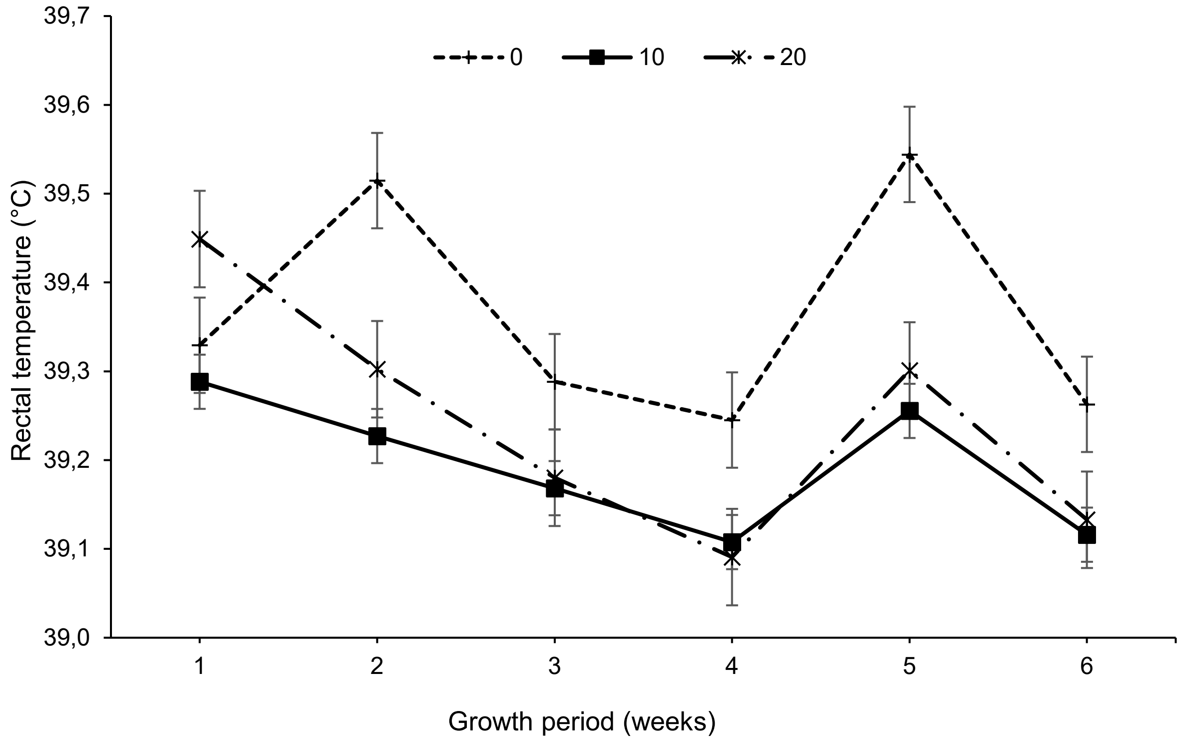

Figure 5.2 Effect of water restriction level on the rectal temperature of selected South African sheep

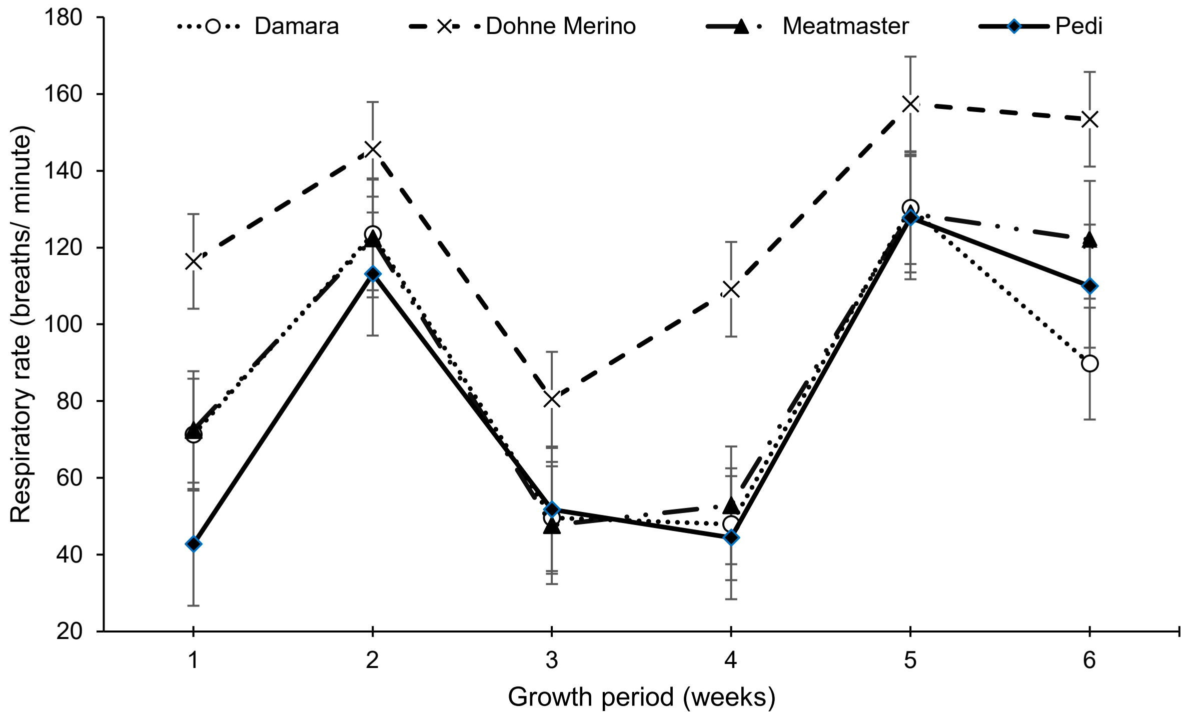

Figure 5.3 Effect of breed on the respiratory rate of selected South African sheep

5.4.2 Effects of water restriction and breed on blood cortisol

No interactive, breed or water restriction were observed for the blood cortisol ($P > 0.05$). The cortisol levels ranged from 28-30.8 nmol L^{-1}, which were all below the serum cortisol values were below 42-82 nmol L^{-1}, which is the normal range for sheep (Jackson and Cockcroft, 2002). The lack of water restriction on the release of serum cortisol has been reported before (Jaber et al., 2004). Cortisol is the primary stress hormone in ruminants, however, tropical indigenous sheep breeds in particular display higher thermotolerance and dehydration (Joy et al., 2020; Silanikove 1992). Provision of shade and the limited movement of sheep in the current study could be the reason why even the exotic composite breed (i.e. Dohne Merino), irrespective of the water restriction level. However, the probability of increased serum cortisol levels is expected as was reported in a study by Casamassima et al. (2016) at higher levels of water restriction.

5.4.3 Effects of water restriction and breed on feed and water intake, growth, and carcass traits of South African sheep

Table 5.3 shows the intake of feed and water, growth and carcass parameters of selected sheep breeds exposed to varying water restriction levels. There were no interactive effects for all water intake parameters, including water drunk, water in feed and daily water intake either as L d^{-1} or as a percentage of live body weight ($P > 0.05$). However, water restriction and breed individually affected water drunk, water in feed and daily water intake as L d^{-1} and as a percentage of live body weight (% LW; $P \leq 0.05$). Dohne Merino had the highest intake of water drunk as L d^{-1} and percentage of live body weight, water in feed (L d^{-1}) and daily water intake (L d^{-1} and %LW), followed by Damara and Meatmaster ($P \leq 0.05$), which did not differ from the Pedi ($P > 0.05$). There is a positive relationship between water and animal live weight, provided the water supply is unlimited. When the daily water intake was expressed as a percentage of the metabolic weight (Fig. 5.3a), breed × water restriction effects were observed ($P \leq 0.05$). The control treatments for all breeds had higher ($P \leq 0.05$) daily water intake as a percentage of the metabolic weight than the other interactions. In general, for all water restriction levels, Dohne Merino had higher ($P \leq 0.05$) daily water intake expressed as a percentage of metabolic body weight ($LW^{0.75}$) than the other interactions. The higher water intake for these treatments could be related to the fact that Dohne Merino is a larger breed (Van der Merwe et al., 2019), and its water consumption, irrespective of restriction levels, would generally be higher than other breed × water restriction interactions.

Overall, indigenous tropical sheep breeds in the tropics can budget their water requirements more economically than exotic breeds and composites (Schoeman and Visser, 1995). Water budgeting of indigenous tropical sheep breeds can partly be explained by the evolutionary adaptation strategies of indigenous breeds to arid conditions, which are characterised by water shortages for most of the year (Ferreira et al., 2002). In addition, minor differences in water intake parameters may be related to the inactivity of individually housed animals, which alters their performance and behaviour (Mupfiga et al., 2022) and lowers their maintenance requirements because of restricted movement (Brand et al., 2017). There was a general decline ($P \leq 0.05$) in the water intake due to water restriction levels in the order of 0% > 10% > 20%. The decline in water intake due to water restriction was expected as animals with the highest water restriction consumed the least amount of water (i.e. water drunk and water in feed). Animals that consume less water will also reduce feed intake (Alamer and Al-Hozab, 2004), which concurs with the DMI intake findings.

No breed × water restriction interactions were observed for DMI ($P > 0.05$). However, DMI was independently affected by water restriction and breed ($P \leq 0.05$). Generally, Damara had the highest DMI, followed by intermediate values for Dohne Merino, and the lowest was observed for the Meatmaster and Pedi in that order ($P \leq 0.05$). The variation could be explained by the differences in the initial weight since animals consume feed based on their body weight. In the feedlot, lambs can consume between 4-5% of their body weight (Mahgoub et al., 2000). Therefore, heavier animals consume more feed than lightweight animals, which could explain the differences in this study. Dry matter intake expressed as a percentage of metabolic body weight ($LW^{0.75}$) showed a breed × water restriction interaction (Fig. 5.3b; $P \leq 0.05$). Apart from Damara (20%) and Dohne Merino (10%), Pedi, Meatmaster and Damara breeds in the 10 and 20% water restriction treatments had less than 9.6% DMI per metabolic weight ($P \leq 0.05$). These findings are higher than those by Mahgoub et al. (2000), which could be due to the breed and diet differences between the two studies. A positive relationship exists between feed intake and the amount of water consumed (Silanikove, 1992). In turn, the proportionality of the changes in feed or water will be influenced by variations in one of these variables (Silanikove, 1992). The DMI as a percentage of live weight surpassed 3.5 to 4.2% for feedlot-fed lambs (Mahgoub et al., 2000; Meat and Livestock Australia, 2017), which could be due to the high-quality energy diet (Sousa et al., 2012). This is despite some animals receiving 80% of their daily water intake. However, the water-restricted groups generally consumed less feed than those on the control treatments because of the reasons mentioned earlier regarding the correlation between feed and water intake.

Reduction of feed intake in water-restricted ruminants is a known phenomenon which permits the animal to conserve limited water (Mupfiga et al., 2022). In water-restricted sheep, feed intake is reduced as a mechanism to reduce costs related to water use in food digestion, subsequently lowering an animal’s metabolic rate (i.e. lower heat dissipation), thereby contributing to water conservation (Alamer and Al-Hozab, 2004; Silanikove, 1992). Therefore, animals can retain sufficient body fluids so that a new equilibrium can be achieved under the prevailing water supply conditions (dos Santos et al., 2019). In addition, voluntary feed intake by ruminants is influenced by the shifts in the osmolality of body fluids due to hypovolemia and hyperosmolality as a result of saliva and gastric juice secretion (Jaber et al., 2013). These mechanisms can influence an animal's desire to drink while feeding and reduce or stop feeding when severely dehydrated (Jaber et al., 2013; Silanikove, 1992).

Table 5.3 Effects of water restriction and breed on intake of feed and water and production of selected South African sheep

Variable	Water restriction (%)				Breed				
	0	10	20	P-Value	Damara	Dohne Merino	Meatmaster	Pedi	P-value
Feed and water intake									
Dry matter intake (DMI; kg d^{-1})	1.5 ± 0.02^{x}	1.4 ± 0.02^{y}	1.3 ± 0.02^{y}	<0.0001	1.5 ± 0.04^{a}	1.4 ± 0.03^{ab}	1.3 ± 0.05^{b}	1.3 ± 0.02^{b}	0.0004
DMI (% body weight; LW)	4.1 ± 0.05^{x}	3.9 ± 0.05^{y}	3.7 ± 0.05^{y}	<0.0001	4.1 ± 0.08^{a}	4.0 ± 0.06^{ab}	3.9 ± 0.11^{ab}	3.7 ± 0.06^{b}	0.0022
Water drunk (mL d^{-1})	3549 ± 63.4^{x}	2996 ± 62.5^{y}	2708 ± 63.7^{z}	<0.0001	3161 ± 101.1^{b}	3610 ± 77.0^{a}	2863 ± 123.6^{bc}	2703 ± 74.1^{c}	<0.0001
Water drunk (% of LW)	9.9 ± 0.17^{x}	8.6 ± 0.17^{y}	7.8 ± 0.17^{z}	0.0140	8.9 ± 0.27^{b}	10. 1 ± 0.21^{a}	8.4 ± 0.34^{bc}	7.7 ± 0.20^{c}	<0.0001
Water in feed (L d^{-1})	361.0 ± 6.45^{x}	304.8 ± 6.36^{y}	275.5 ± 6.47^{z}	<0.0001	321.5 ± 10.29^{b}	367.2 ± 7.83^{a}	291.3 ± 12.57^{bc}	275.0 ± 7.53^{c}	<0.0001
Daily water intake (DWI; L d^{-1})	3910 ± 69.8^{x}	3301 ± 68.8^{y}	2984 ± 70.1^{z}	<0.0001	3482 ± 111.4^{b}	3977 ± 84.8^{a}	3154 ± 136.1^{bc}	2978 ± 81.6^{c}	<0.0001
DWI (% of LW)	10.9 ± 0.19^{x}	9.5± 0.19^{y}	8.62 ± 0.19^{z}	<0.0001	9.8 ± 0.30^{b}	11.2 ± 0.23^{a}	9.3 ± 0.37^{bc}	8.5 ± 0.22^{c}	<0.0022
Weight measurements									
Final weight (kg)	44.3 ± 0.74^{x}	42.9 ± 0.74^{xy}	41.6 ± 0.75^{y}	0.0502	49.7 ± 0.85^{a}	46.3 ± 0.87^{b}	43.8 ± 0.85^{b}	31.9 ± 0.85^{c}	<0.0001
ADG (g)	318.3	295.9	275.1	0.0959	337.4 ± 22.4^{a}	304.3 ± 17.16^{ab}	292.2 ± 16.43^{bc}	251.9 ± 27.57^{c}	0.0464
Feed and water efficiency									
Feed conversion ratio	4.7 ± 0.15	4.6 ± 0.15	4.8 ± 0.15	0.8234	5.1 ± 0.17^{a}	4.3 ± 0.17^{b}	4.8 ± 0.17^{ab}	4.7 ± 0.17^{ab}	0.0141
Water to gain ratio	10.5 ± 0.31	10.1 ± 0.30	9.8 ± 0.31	0.2638	10.5 ± 0.34	10.3 ± 0.36	10.0 ± 0.36	9.59 ± 0.34	0.2360
Carcass traits									
Hot carcass weight (kg)	21.7 ± 0.39	21.1 ± 0.39	20.5 ± 0.39	0.1024	23.8 ± 0.45^{a}	22.7 ± 0.46^{a}	22.7 ± 0.45^{a}	15.2 ± 0.45^{b}	<0.0001
Dressing percentage	49.0 ± 0.41	49.3 ± 0.41	49.1 ± 0.42	0.8791	47.8 ± 0.48^{b}	49.0 ± 0.49^{b}	51.9 ± 0.48^{a}	47.7 ± 0.47^{b}	<0.0001
Economic analysis									
Feed cost[1#]	326.2 ± 5.76^{x}	291.9 ± 5.76^{y}	277.3 ± 5.86^{y}	<0.0001	355.4 ± 6.65^{a}	318.0 ± 6.81^{b}	289.6 ± 6.65^{c}	230.9 ± 6.66^{d}	<0.0001
Income[2]	2018.6 ± 40.08	2040.6 ± 46.08	1955.0 ± 46.89	0.4056	1925.8 ± 53.20^{b}	2313.5 ± 54.46^{a}	2263.5± 53.20^{a}	1516.3 ± 53.20^{c}	<0.0001
IOFC[3]	1692.6 ± 43.19	1748.7 ± 43.19	1677.7 ± 43.96	0.4790	1570.4 ± 49.87^{b}	1995.4 ± 51.05^{a}	1973.9 ± 49.87^{a}	1285.4 ± 49.87^{c}	<0.0001

$^{x\text{-}y}$ For water restriction levels: least square means in a row without a common letter differ significantly by the Tukey-Kramer test (P ≤ 0.05). $^{a\text{-}c}$ For breed: least square means in a row without a common letter differ significantly by the Tukey-Kramer test (P ≤ 0.05). * DWI is the average of water drunk and water intake from the feed. [1] Total feed costs = cost per kg of feed × dry matter intake; #The cost of one kg of feed was R5.81 [2]Total income = income generated after selling cold carcass; [3]Income over feed cost = Total income-Total feed costs; The carcass prices prevailing at the time of slaughter are according to the (Red Meat Abattoir Association, 2022).

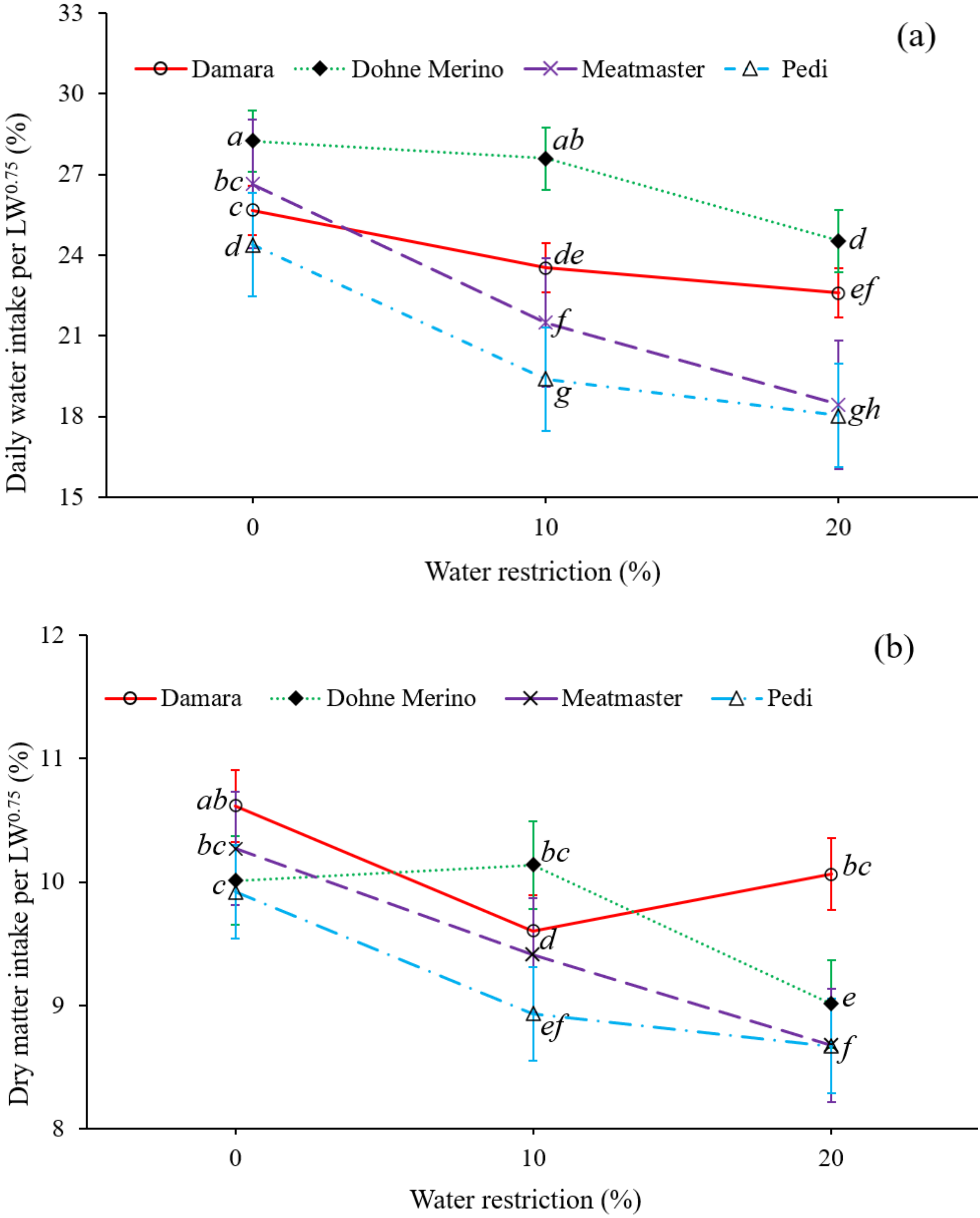

Figure 5.4 Interactive effect of water restriction and breed on the proportion of (a) daily water intake and (b) dry matter intake per metabolic body weight ($LW^{0.75}$)

Irrespective of breed, there was a general decline in the final live weights for water restriction in the order of 0% ≥ 10% ≥ 20% ($P \leq 0.05$). The influence of water restriction on final live weights can be explained by its influence on DMI, as explained earlier. However, ADG tended ($P < 0.10$) to decrease with an increase in water restriction. Interestingly, up to 20%, water restriction did not negatively affect the final live weight and ADG. No breed × water restriction interactive effects were observed for the final live weight and ADG ($P > 0.05$); however, the former was influenced ($P \leq 0.05$) by water restriction and breed, while the latter was affected ($P \leq 0.05$) by breed only. The Damara, a pure indigenous tropical breed, had the highest final live weight and ADG, followed by the composite breeds (i.e. Dohne Merino and Meatmaster), whilst another pure indigenous (i.e. Pedi) breed had the least final live weight and ADG ($P \leq 0.05$). Damara is known for its rapid-growing ability (Almeida, 2011), which could have further been enhanced by consuming a high-energy diet. These results concur with reports by (Mupfiga et al., 2022), who reported higher ADG for the Damara and Meatmaster. The exceptional performance of these two breeds compared to the traditional feedlot breed (i.e. Dohne Merino) could be related to their close genetic ties as the Meatmaster was bred by crossing Damara as a maternal line and crossing with Il de France, Dorper and South African Meat Mutton breeds (Almeida, 2011; Peters et al., 2010).

Water restriction had no effect ($P > 0.05$) on FCR and water-to-gain ratio. However, FCR was influenced by breed, with a Damara having higher ($P \leq 0.05$) values than Dohne Merino ($P \leq 0.05$), but the values for both breeds were not different ($P > 0.05$) from that of Meatmaster and Pedi. However, the FCR for all the breeds is consistent with the nutrient requirements of domesticated sheep regarding their economic viability under feedlot conditions (Cannas et al., 2019; Keogh et al., 2022). The variation between the highest and lowest FCR was 15.6%, which was lower than that reported by (Mupfiga et al., 2022). Neither breed, water restriction, nor their interaction affected the water-to-gain ratio ($P > 0.05$). A lower water-to-gain ratio would be ideal because animals having low water and feed intakes but maintaining optimal weight gains are favourable, as this would likely increase producers' financial returns.

Water restriction did not affect hot carcass weight and dressing percentage ($P > 0.05$). Breed influenced the hot carcass weight, with Pedi having lower ($P \leq 0.05$) values than the other three breeds, which were not different ($P > 0.05$) from each other. The carcass weight of animals fed the same nutritional regime highly depends on their genotype (Scanlon et al., 2013). The lower carcass weight for Pedi was anticipated because of its smaller final live weight compared to the rest of the breeds. Despite the differences in the final weight, no differences in hot carcass weight were observed between Damara, Dohne Merino and Meatmaster. Meatmaster had a higher ($P \leq 0.05$) dressing percentage than the rest of the breeds. However, all breeds were within the expected range (i.e. 44-56%) for sheep (Wilkes et al., 2012). The variation in dressing percentage could be ascribed to maturity patterns in sheep (Hopkins, 1992), amongst other factors. The fast growth rate (Litherland et al., 2010) of Meatmaster, a novel and early maturing breed, could account for its higher dressing percentage.

There was no association between water restriction with carcass age, fatness and conformation classifications (Table 5.4; $\chi^2 = 7.7$; $P > 0.05$; $\varphi = 0.2022$). However, there was an association between breed with carcass classification (Table 5.4; $\chi^2 = 77.1$; $P \leq 0.05$; $\varphi = 0.5203$). All breeds were classed as young (A), with differences observed for fatness (South African Meat Industry Company, 2006). Across breeds, 41% of the carcasses were classed as lean, with Dohne Merino contributing over half of these, followed by Meatmaster, Pedi and the Damara with the lowest ($P \leq 0.05$). A quarter of the carcasses were classed as having medium fat, with Pedi having the greatest proportion, followed by Meatmaster ($P \leq 0.05$), whilst the Damara and Dohne Merino had the least proportion not different ($P > 0.05$) from each other (Table 5.4). Apart from the Dohne Merino, the rest of the breeds (33%) classed from fat to excessively over-fat, with the Damara accounting for 12.6% of the carcasses in the excessively over-fat class (Table 5.4). The differences in the carcass fatness levels among the breeds can be ascribed to the differences in breed maturity (Van der Merwe et al., 2020a, 2020b). Early maturing (i.e. Damara, Meatmaster and Pedi) deposit fat at an earlier stage compared to the medium-maturing (i.e. Dohne Merino) breeds (Van der Merwe et al., 2020a). Therefore, early maturing breeds should be slaughtered at a lighter live weight than medium- or late-maturing breeds for the producers to have more of the carcass classed as young and lean (A2). Producing more A2 animals aligns with consumer demands for lean lamb meat that still retains appropriate fat to meet food quality requirements.

Table 5.4 Proportion (%) of different carcass age and fatness classes of South African sheep

Class	Breed				
	Damara	Dohne Merino	Meatmaster	Pedi	Total
A1	-	1.05 (1)	-	-	1.05 (1)
A2	2.11 (2)	21.05 (20)	9.47 (9)	8.42 (8)	41.05 (39)
A3	2.11 (3)	2.11 (3)	9.47 (9)	11.58 (11)	25.26 (24)
A4	6.32 (6)	-	6.32 (6)	4.21 (4)	16.84 (16)
A5	2.11 (2)	-	-	1.05 (1)	3.16 (3)
A6	12.63 (12)	-	-	-	12.63 (12)

NOTE: The number in parenthesis indicates the number of carcasses.

Animals on water-restricted treatment had lower ($P \leq 0.05$) feed costs than the control group because of the reduced DMI discussed earlier. However, water restriction did not influence ($P > 0.05$) income and IOFC. These parameters are affected by the price of the carcasses, which were not influenced by water restriction. Damara had the highest feed costs, followed by Dohne Merino, Meatmaster and Pedi ($P \leq 0.05$). This trend followed that for DMI, which played a significant role in the differences, as feed prices were constant across breeds. Feed costs were calculated based on the actual intake; therefore, an animal that consumes more feed will have a higher feed cost. Income from sales of carcasses and income-over-feed-cost (IOFC) were in the order of Dohne Merino = Meatmaster > Damara > Pedi ($P \leq 0.05$). Their higher income for Dohne Merino could be attributed mainly to their greater number of A2 carcasses (Table 5), which is the premium class in South Africa (Van der Merwe et al., 2020b). In contrast, Meatmaster's contribution is due to the heavier carcass and the generally lower feed cost, even though it had fewer carcasses in the A2 class. Although Pedi had the lowest feed costs, its income and IOFC can primarily be attributed to its lightweight carcasses and classification of carcasses into lower premium classes (Table 5.4).

5.4.4 Effect of water restriction and breed on meat physicochemical traits of South African lamb meat

None of the meat physicochemical parameters was influenced by breed × water restriction interaction. The effects of water restriction and breed on meat physicochemical parameters are presented in Table 5.5. Moisture content was influenced by water restriction, with the control and 20% water restriction groups having greater ($P \leq 0.05$) values, but there is no difference ($P > 0.05$) between the control and the 10% water restriction. These differences between the water restriction groups were less than 1.2%, hence are minor as the moisture content was still within the expected percentage (~75%) for lamb meat (dos Santos et al., 2019; López-Bote, 2017). The IMF was influenced by breed ($P \leq 0.05$), while water restriction had no effect ($P > 0.05$). The IMF content followed the order Dohne Merino ≥ Meatmaster ≥ Damara = Pedi ($P \leq 0.05$). The higher IMF for the Damara, Dohne Merino and Meatmaster could be attributed to the animals' weight. The final live weights in the current study are generally above the ideal weights required to maximise profits in the South African feedlot system (Van der Merwe et al., 2020b). It should be noted that the IMF contents of all the breeds in the current study are within the 2.5% expected for lambs (Holman and Hopkins, 2021; López-Bote, 2017). Meat protein and ash neither affected breed nor water restriction ($P > 0.05$).

Water restriction and breed affected the carcass temperature at 45 minutes ($P \leq 0.05$). The control group had a lower ($P \leq 0.05$) temperature at 45 min than the 20% water restriction group, which was attributed to differences in carcass weights which tended to decline with increasing water restriction levels. Dohne Merino had the highest temperature at 45 min, with intermediate values for the Meatmaster and Damara, whereas the Pedi had the lowest ($P \leq 0.05$). This could be because smaller carcasses cool faster than large ones (Warriss, 2010). Neither water restriction nor breed influenced ($P > 0.05$) carcass temperature at 45 minutes.

Water restriction influenced ($P \leq 0.05$) pH 45, with the 20% group having lower ($P \leq 0.05$) values than the control and 10% groups. There is no immediate explanation as to why the 20% water restriction group had higher pH than the other groups. Current results contrast earlier findings (Araújo et al., 2022; Jones et al., 1990), which have reported that water restriction does not affect pH in ruminants. The lower pH at 45 min and 24 h ($P \leq 0.05$) observed for the Dohne Merino compared to the rest of the breeds could be attributed to genotypic effects related to genes associated with a greater sensitivity to stress in lambs destined for slaughter (Gardner et al., 1999). The Merinos reportedly have lower pH than other genotypes (Cloete et al., 2012; Hoffman et al., 2003; Hopkins and Fogarty, 1998). The ultimate pH (pH at 24 h) for all breeds was less than 5.8, beyond which lamb meat is undesirable owing to its dark, firm and dry characteristics (Hoffman et al., 2003).

Water restriction and breed did not influence the cooking losses ($P > 0.05$), which concurs with the findings by Araújo et al. (2022) and dos Santos et al. (2019). The cooking loss values ranged between 34.3 and 35.6, greater than the previous studies (Araújo et al., 2022; dos Santos et al., 2019), ranging from 28.0 to 31.3%. Variation among these values could be attributed to the duration of the water restriction between the three studies. Similarly, the WBSF was not influenced by any fixed factors ($P > 0.05$). All the breeds had values below 49.0 N, considered tender for lamb meat (Hopkins et al., 2006).

Meat lightness (L^*) and yellowness were affected by breed, whilst water restriction only affected meat redness (a^*) ($P \leq 0.05$). Dohne Merino had higher ($P \leq 0.05$) L^* values than the rest of the breeds, which was attributed to their higher IMF content and lower pH_{24} than the other breeds. Despite the susceptibility of Merino lambs to produce meat with a higher pH than other types, they usually produce lighter-coloured meat (Hopkins and Mortimer, 2014). The values reported in the current study are lower than those reported by Araújo et al. (2022) in ewes restricted water at 20% and above 34, the threshold acceptable by consumers for lamb meat (Khliji et al., 2010). No immediate explanation as to why there was an increase in a^* as the water restriction level increased to 20%. An Australian study showed that consumers accept lamb meat at a threshold of not less than a lamb meat redness threshold value of 9.5 (Khliji et al., 2010). Meat yellowness followed the order of Dohne Merino, Meatmaster, Damara and Pedi ($P \leq 0.05$), which could be due to disparities in the muscle density of the different genotypes as animals with low muscle density, including the Merinos have been reported to have higher yellowness values (Thomas et al., 2021).

Table 5.5 Effect of water restriction and breed on carcass on physicochemical attributes of selected South African sheep meat.

	Water restriction (%)			Breed				P value	
Meat physicochemical attribute	0	10	20	Damara	Dohne Merino	Meatmaster	Pedi	Water restriction	Breed
Moisture	75.1 ± 0.18^{xy}	74.9 ± 0.18^{y}	75.7 ± 0.18^{x}	75.5 ± 0.21	75.4 ± 0.21	75.1 ± 0.21	75.1 ± 0.21	0.0169	0.3426
Crude protein	22.0 ± 0.20	22.2 ± 0.19	21.6 ± 0.19	22.0 ± 0.22	21.8 ± 0.23	21.9 ± 0.22	22.1 ± 0.22	0.0972	0.8989
Fat	2.7 ± 0.12	2.6 ± 0.12	2.4 ± 0.12	2.4 ± 0.14^{b}	2.9 ± 0.14^{a}	2.7 ± 0.14^{a}	2.2 ± 0.14^{b}	0.1458	0.0027
Ash	1.1 ± 0.01	1.1 ± 0.01	1.1 ± 0.01	1.1 ± 0.01	1.1 ± 0.01	1.1 ± 0.01	1.1 ± 0.01	0.6937	0.2560
Temperature (45 mins)	28.6 ± 0.19^{x}	28.3 ± 0.19^{xy}	27.9 ± 0.19^{y}	27.8 ± 0.22^{bc}	29.4 ± 0.22^{a}	28.3 ± 0.22^{b}	27.5 ± 0.22^{c}	0.0477	<0.0001
Temperature (24 h)	5.3 ± 0.13	5.5 ± 0.13	5.2 ± 0.13	5.1 ± 0.15	5.3 ± 0.15	5.2 ± 0.15	5.5 ± 0.15	0.2592	0.1013
pH (45 mins)	6.4 ± 0.04^{y}	6.4 ± 0.04^{y}	6.5 ± 0.04^{x}	6.5 ± 0.04^{a}	6.2 ± 0.04^{b}	6.4 ± 0.04^{a}	6.5 ± 0.04^{a}	0.0507	<0.0001
pH (24 h)	5.5 ± 0.05	5.5 ± 0.05	5.5 ± 0.05	5.6 ± 0.06^{a}	5.4 ± 0.06^{b}	5.5 ± 0.06^{ab}	5.6 ± 0.06^{a}	0.1332	0.0465
Cooking loss (%)	34.4 ± 0.81	35.6 ± 0.83	35.0 ± 0.86	34.3 ± 0.97	35.2 ± 0.98	35.2 ± 0.93	35.2 ± 0.97	0.6054	0.8843
Warner-Bratzler Shear Force (N)	35.1 ± 2.35	33.7 ± 2.35	32.3 ± 2.35	36.6 ± 2.72	29.2 ± 2.72	36.7 ± 2.72	32.3 ± 2.72	0.6986	0.1630
Lightness (L^*)	36.7 ± 0.37	36.9 ± 0.37	36.8 ± 0.38	35.9 ± 0.43^{b}	38.2 ± 0.43^{a}	36.4 ± 0.43^{b}	36.7 ± 0.43^{b}	0.9574	0.0016
Redness (a^*)	13.2 ± 0.58^{y}	13.4 ± 0.58^{y}	14.1 ± 0.59^{x}	13.4 ± 0.67	14.3 ± 0.68	13.5 ± 0.67	13.0 ± 0.67	0.5000	0.5877
Yellowness (b^*)	9.6 ± 0.26	9.8 ± 0.26	9.5 ± 0.26	9.5 ± 0.30^{ab}	10.1 ± 0.30^{a}	9.9 ± 0.30^{ab}	8.9 ± 0.30^{b}	0.7122	0.0304

$^{a-c}$ For breed: least square means in a row without a common letter differ significantly by the Tukey-Kramer test (P ≤ 0.05).
$^{x-y}$ For water restriction levels: least square means in a row without a common letter differ significantly by the Tukey-Kramer test (P ≤ 0.05).

5.4.5 Effect of water restriction and breed on the sensory quality of South African lamb meat

The effect of water restriction and breed on the aroma, flavour and textural attributes of selected South African lamb meat are presented in Table 5.6. Neither water restriction nor breed × water restriction interaction was significant concerning all the sensory attributes ($P > 0.05$). Metallic was the only aroma attribute influenced by breed, with Dohne Merino and Meatmaster having the highest values ($P \leq 0.05$), however, the latter did not differ from either Damara or Pedi ($P > 0.05$). The metallic aroma differences across breeds were not immediately apparent, as this attribute is often associated with raw meat. Pedi had lower ($P \leq 0.05$) lamb meat and fat flavour than the rest of the breeds, with the former having greater intensity than the latter. Lamb meat or fat flavour is common in sheep-fed concentrate diets because of the usually higher IMF content (Resconi et al., 2009). Lamb fat flavour is a derivative of the 2,4-decadienal volatile compound which develops with the presence of α-linoleic acid (Resconi et al., 2009). The livery flavour was highest in the Meatmaster and lowest in Damara ($P \leq 0.05$), which could be related to the variation in volatile compounds such as hexanol and heptanal (Calkins and Hodgen, 2007). Damara and Dohne Merino had higher ($P \leq 0.05$) scores for rancid flavour than Meatmaster and Pedi. Lipid oxidation is responsible for the development of unpleasant flavours (e.g. rancid) in stored meat because of the presence of rancidity initiators amongst them transition metal ions (e.g. Fe^{n+} and Cu^{n+}; Resconi et al., 2013). In addition, roasting leads to the development of volatile compounds such as (*E*)-nonenal and (*E*,*E*)-2,4-decadienal, which can also contribute to rancid flavour (Resconi et al., 2013). However, in the current study, the low rancid flavour scores could be ascribed to the low rate of lipid oxidation as the loins were stored at -20°C for one month before sensory evaluation. Lipid oxidation can still occur under freezing temperatures leading to the development of rancid flavours (Hagyard et al., 1993). The detection of the rancid aroma and liver flavour adversely affects consumer acceptability.

Tenderness, mealiness, residue and fatty mouthfeel textural attributes were influenced by breed ($P \leq 0.05$). Dohne Merino had more tender ($P \leq 0.05$) meat than Damara and Pedi ($P > 0.05$). Variations in IMF contents might have contributed to meat tenderness by diluting the connective tissue of elements in the muscle in which it is deposited (Dunshea et al., 2021). Meat tenderness is also influenced by many factors (e.g. sarcomere shortening during rigor development, amount and solubility of connective tissue and post-mortem proteolysis of myofibrillar and myofibrillar-associated proteins), which interact in a non-linear manner (Warner et al., 2010). Although none of these factors were quantified in the current study, they could have contributed to meat tenderness, considering the diverse nature of the lamb genotypes.

Dohne Merino had a higher ($P \leq 0.05$) mealiness texture than the rest of the breeds. Mealiness is considered a negative attribute due to the crumbling of muscle fibres within the first few chews, which is often associated with older animals (Hoffman, 2006). However, the differences in mealiness scores across breeds were low in the current study, thus of minor significance. The Damara, Pedi and Meatmaster had greater ($P \leq 0.05$) residue content than the Dohne Merino. The high residue score observed for these breeds could be associated with less tender meat (Erasmus et al., 2016). This is possible because these breeds are either indigenous or were developed from indigenous genetic lines, which are usually associated with less tender meat. Dohne Merino and Meatmaster had greater ($P \leq 0.05$) fatty mouthfeel scores than Damara and Pedi. This could be related to the higher IMF contents reported for these two breeds, which contributes to higher energy. Intuitively, a fatty mouthfeel signals high-energy foods because it activates neural reward centres (Cox et al., 2018).

Table 5.6 Effect of water restriction and breed on sensory quality parameters (mean ± standard deviation) of the *longissimus thoracis et lumborum* of selected South African sheep breeds

Sensory attribute	Water restriction (%)			Breed				P value	
	0	10	20	Damara	Dohne Merino	Meatmaster	Pedi	Water restriction	Breed
Aroma									
Lamb meat	70.4 ± 1.86	70.7 ± 2.52	70.3 ± 1.78	70.8 ± 1.77	70.5 ± 1.667	70.9 ± 2.11	69.7 ± 2.32	0.8031	0.3407
Lamb fat	22.2 ± 1.15	22.27 ± 1.46	22.3 ± 1.27	22.0 ± 0.99	22.6 ± 1.49	22.7 ± 1.14	21.8 ± 1.32	0.9912	0.1221
Metallic	19.0 ± 1.51	18.7 ± 1.74	18.5 ± 1.55	18.2 ± 1.44^{b}	19.1 ± 1.56^{ab}	19.5 ± 1.72^{a}	18.3 ± 1.34^{b}	0.5128	0.0284
Herbaceous	22.0 ± 0.87	21.9 ± 1.03	21.7 ± 0.91	21.7 ± 0.89	21.9 ± 0.72	21.2 ± 0.82	21.7 ± 1.22	0.5303	0.3062
Sweet-associated	21.5 ± 0.82	21.3 ± 1.07	21.2 ± 1.02	21.2 ± 0.84	21.5 ± 0.78	21.6 ± 1.09	21.0 ± 1.09	0.6974	0.2911
Savoury broth	21.4 ± 0.37	21.2 ± 0.52	21.3 ± 0.46	21.1 ± 0.44	21.3 ± 0.33	21.4 ± 0.51	21.2 ± 0.49	0.2745	0.2229
Barnyard kraal	6.2 ± 1.44	5.9 ± 1.733	6.0 ± 1.91	5.5 ± 1.79	6.3 ± 1.40	6.5 ± 1.79	6.0 ± 1.70	0.7924	0.2760
Liver	2.9 ± 1.08	2.9 ± 1.62	3.1 ± 1.14	2.4 ± 0.90	3.2 ± 0.94	3.3 ± 1.26	3.0 ± 1.20	0.7398	0.0763
Rancid	0.05 ± 0.039	0.03 ± 0.036	0.03 ± 0.036	0.04 ± 0.038	0.04 ± 0.036	0.04 ± 0.042	0.03 ± 0.034	0.4052	0.7927
Flavour									
Lamb meat	69.7 ± 1.76	70.2 ± 2.19	70.3 ± 2.30	70.2 ± 2.04^{a}	70.4 ± 1.82^{a}	71.0 ± 1.68^{a}	68.8 ± 2.26^{b}	0.5299	0.0123
Lamb fat	22.3 ± 0.84	22.5 ± 0.96	22.3 ± 1.01	22.3 ± 0.73^{b}	22.3 ± 1.12^{ab}	22.9 ± 0.80^{a}	21.9 ± 0.82^{b}	0.7576	0.0203
Metallic	21.2 ± 0.97	21.3 ± 1.09	20.9 ± 0.84	21.1 ± 1.01	21.2 ± 0.91	21.5 ± 1.06	20.9 ± 0.88	0.3017	0.1848
Herbaceous	22.9 ± 0.61	23.1 ± 0.73	22.7 0.73	22.9 ± 0.62	22.9 ± 0.72	22.9 ± 0.73	22.8 ± 0.77	0.1993	0.9771
Sweet-associated	20.4 ± 0.83	20.4 ± 0.86	20.5 ± 1.07	20.5 ± 0.83	20.5 ± 0.98	20.6 ± 0.81	20.1 ± 1.01	0.9427	0.3801
Savoury broth	21.3 ± 0.57	21.4 ± 0.78	21.4 ± 0.93	21.4 ± 0.60	21.4 ± 0.82	21.5 ± 0.76	21.2 ± 0.88	0.7707	0.5193
Barnyard kraal	6.3 ± 1.31	6.0 ± 1.33	5.9 ± 1.55	6.0 ± 1.29	5.87 ± 1.29	6.3 ± 1.42	6.0 ± 1.63	0.6195	0.8529
Liver	3.7 ± 1.40	3.1 ± 0.74	3.7 ± 0.85	3.0 ± 0.70^{b}	3.6 ± 1.24^{ab}	3.98 ± 0.95^{a}	3.5 ± 1.12^{ab}	0.0860	0.0443
Rancid	0.04 ± 0.034	0.05 ± 0.041	0.04 ± 0.040	0.06 ± 0.034^{a}	0.06 ± 0.038^{a}	0.03 ± 0.039^{b}	0.03 ± 0.035^{b}	0.5027	0.0163
Salty taste	20.7 ± 0.34	20.6 ± 0.31	20.5 ± 0.27	20.7 ± 0.33	20.6 ± 0.31	20.6 ± 0.23	20.5 ± 0.36	0.1462	0.2603
Textural									
Tenderness	67.2 ± 9.75	65.8 ± 8.91	70.2 ± 8.03	64.6 ± 9.33^{b}	72.5 ± 5.40^{a}	68.9 ± 8.82^{ab}	64.9 ± 10.1^{b}	0.1918	0.0209
Sustained juiciness	52.8 ± 3.75	53.2 ± 3.93	53.8 ± 3.65	51.9 ± 3.92	54.6 ± 2.08	54.0 ± 3.65	52.6 ± 4.55	0.6322	0.1311
Mealiness	7.3 ± 2.66	7.1 ± 2.98	7.9 ± 1.52	7.2 ± 3.16^{b}	8.8 ± 1.46^{a}	7.2 ± 2.23^{b}	6.6 ± 2.27^{b}	0.4393	0.0345
Residue	15.2 ± 7.44	15.4 ± 8.13	12.3 ± 5.64	17.5 ± 10.02^{a}	10.0 ± 3.27^{b}	13.8 ± 7.35^{ab}	15.9 ± 7.51^{a}	0.2212	0.0110
Fatty mouthfeel	6.2 ± 0.81	6.6 ± 0.86	6.5 ± 0.74	6.1 ± 0.80^{b}	6.7 ± 0.78^{a}	6.8 ± 0.53^{a}	6.1 ± 0.87^{b}	0.3072	0.0083

[a-c] In each row, the least square means without a common letter differ significantly by the LSD ($P \leq 0.05$).

5.5 Conclusions

Water restriction slightly reduced final live weight and increased meat redness without adversely influencing growth, carcass, and meat quality attributes. Meatmaster and Pedi had lower daily water intake than Dohne Merino. Compared to other breeds, Meatmaster and Dohne Merino had superior carcass weights, income-over-feed-costs, the lowest carcass pH, and the most tender meat. Feed intake, average daily gain, and feed costs were higher in Damara than in Pedi and Meatmaster. Pedi had lighter and leaner carcasses and lower lamb meat, fat and rancid flavour scores than other breeds. It was concluded that water restriction up to 20% has no adverse effects on meat production and quality, and Meatmaster could be the ideal feedlot breed under water-scarce conditions.

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CHAPTER 6 - OVERALL CONCLUSIONS, DISCUSSIONS AND RECOMMENDATIONS

6.1 Conclusions and discussions

In South African agriculture, sheep farming plays a major role in the production of various animal products (i.e. fibre, meat, and dairy) and their rearing is often embedded in people's culture and beliefs, making them a significant sustainable livelihood option for resource-limited producers. However, water scarcity poses a significant challenge to sheep production in arid and semi-arid regions, and the issue is expected to worsen in the future because of climate change. The first part of the study revealed that the likelihood of farmers to perceive the positively impact of water scarcity on sheep production increased with a unit increase in private commercially oriented arid farms, males, education level, adapted breeds and flock size. Although farmers implemented various drought mitigatory strategies, it was important to identify contextual factors determining farmers' perceptions of impacts of water scarcity on sheep production, which should be considered when formulating resilience and adaptive capacity enhancing technologies and policies for smallholder farmers in dry ecozones.

A significant amount of vertical integration is occurring in sheep production, with most large feedlots having their own abattoirs. Since the genetics of sheep determine meat production and quality traits, it is imperative for producers and feedlotters to utilise breed that can drink less water or tolerate water stress. This informed the current field trials, which evaluated the water requirements, production performance, and meat quality attributes of one exotic (Merino), two indigenous (Pedi and Damara) and three composite (Dohne Merino, Dorper and Meatmaster) South African sheep breeds. The feed intake and growth performance were greater for the Meatmaster and Damara than the other breeds. However, the water balance for these two breeds was comparable to that of the Dohne Merino and Dorper. The Damara and Pedi were more water and feed efficient despite them having inferior carcass attributes and economic returns than other breeds. Indigenous breeds had leaner meat and comparable oxidative shelf life and sensory quality characteristics to composite breeds under intensive feeding conditions.

The last activity investigated how water restriction (0, 10 and 20%) and breed (Damara, Dohne Merino, Meatmaster and Pedi) influences meat production and quality attributes under South African feedlot conditions. No interactive effects of water restriction and breed were observed on meat production and quality parameters during the trial. In this study, Meatmaster and Pedi had lower daily water intake than Dohne Merino. However, Damara had higher feed intake and average daily gain than in Pedi and Meatmaster. Thus, Damara and Pedi are appropriate feedlot breeds for arid regions where water and feed are very scarce. Meatmaster had superior water utilisation efficiency like indigenous breeds but had had superior meat production and quality attributes comparable to the Merinos. Overall, no adverse effects on meat production and quality for water restrictions up to 20%.

It was concluded that feedlotting the Meatmaster breed and subjecting lambs to water restriction up to 20% in the feedlot are potential water-saving strategies for South African sheep farmers. Given that water scarcity in South Africa is predicted to worsen, these water-saving strategies should target farmers with low drought adaptive capacity, particularly less educated women entirely relying on livestock income and farming extensively with non-adapted breeds in the semi-arid ecozones of South Africa.

6.2 Recommendations for further studies

Future investigations on the efficiency of the identified water scarcity response strategies for subsistence and commercial farmers is indispensable. With the predicted water challenges in South Africa, it is important for further research to evaluate other indigenous and composite breeds and higher levels of water restriction, which will enable the determination of the threshold levels beyond which either meat production or quality is compromised. This will allow enable producers, especially those with low drought adaptive capacity to be able to save water without adversely compromising sheep meat production and quality.

Appendix 1: Sheep survey questionnaire

Survey of perceptions and response strategies of smallholder sheep producers to water scarcity in the Cape Provinces of South Africa

The overall objective of the current study will be to investigate perceptions and response strategies of smallholder sheep farmers to water scarcity in South Africa. Farmers' perceptions of impacts of water scarcity could be important in informing decision makers on its causes, impacts and coping strategies perceived at local and national levels for sustainable sheep production. That could significantly contribute towards reducing vulnerability to water scarcity and improve food security for smallholder sheep farmers.

A. General information

1. Name of the farmer…………………………………………………………………
2. Municipality name ……………………….. Community name ……………………
3. Gender of head of household 1= male ☐ 2= female ☐
4. Age of head of household 1= < 30 ☐ 2= 30-49 ☐ 3= 50-70 ☐ 4= >70 ☐
5. Highest education level 1=No formal education☐ 2=Primary☐ 3=Secondary☐ 4=Tertiary☐
6. Religion 1= Christianity ☐ 2= Islam ☐ 3=Traditional ☐ 4= none ☐
7. How much arable land do you own? …………………………………………………
8. How much land is used for grazing and pastures? ……………..……………………
9. What are your major sources of income? (Tick and rank, 1= most important source of income)

Source	Tick	Rank
Crops sales		
Livestock sales		
Salary/wages		
Pension		
Social grants		
Other (specify)		

10. What type of livestock species do you keep? (Rank, 1= most important).

Species	Sheep	Cattle	Goats	Chickens	Pigs	Other (specify)
Number						
Rank						

B. Sheep production system

11. What is the composition of your sheep flock?

Class	Number
Ewes	
Rams	
Lambs	
Ewe lambs	
Castrated lambs	
Ram lambs	

12. What breeds of sheep do you keep? 1= Dorper ☐ 2= Dormer ☐ 3= Merino ☐ 4= South African Mutton Merino ☐ 5= Dohne Merino ☐ 6=Afrino ☐ 7= Damara ☐ 8= Other (specify)…………

13. Which breed do you prefer to farm with? 1= Dorper ☐ 2= Dormer ☐ 3= Merino ☐ 4= South African Mutton Merino ☐ 5= Dohne Merino ☐ 6= Afrino ☐ 7= Damara ☐ 8=Non-Descript/Cross-breeds ☐ 9= Meatmaster ☐

14. Why do you prefer that particular breed? 1= better adapted to environment ☐ 2= high productivity (wool, meat, milk, slaughter lambs) ☐ 3= breeding ☐ 4= cultural ☐ 5= better adapted to environment/high productivity ☐

15. What are your reasons for keeping sheep? (tick the use; and rank: 1 = most important)

Use	Tick	Rank	Use	Tick	Rank
Meat			Cash		
Milk			Status		
Increase flock			Dowry		
Manure			Culture		
Skin			Festivities		
Wool			Other (specify)		

16. What system of production do you use? 1= feedlot/intensive ☐ 2= Semi-intensive ☐ 3= Extensive/Free range ☐ 4= Other (specify)…………………………………………

17. What type of housing do you use? 1= Kraal ☐ 2= None ☐ 3= Other (specify)………

C. Farmers' awareness of water scarcity challenge

18. Do you experience the water scarcity challenge at your farm?1= Yes ☐ 2= No ☐

19. If yes, how frequently do you experience the challenge?1= every year 2= every 5 years ☐ 3= every 10 years ☐4= every 15 years ☐5= > 20 years ☐

20. What is the extent of the challenge? 1= High ☐ 2= moderate ☐ 3= low ☐ 4= don't know ☐

21. Has the water scarcity challenge changed over the past 5 years? 1= Increased ☐ 2= decreased ☐ 3= no change ☐ 4= don't know ☐ 5= flactuates ☐

22. If increased, what are the causes? 1= low rainfall ☐ 2= evaporation ☐ 3= don't know ☐ 4= low rainfall/broken pumps/dry boreholes ☐

D. Effects of water scarcity on water availability and quality for animals

23. Is availability of drinking water a challenge for your sheep? 1= Yes ☐ 2= No ☐

24. If yes, how frequently do you experience the challenge? 1= Seasonally ☐ 2= All year round ☐ 3= Others (specify)………………..……………………………………….

25. Has the availability changed over the past 5 years? 1= decreased ☐ 2= increased ☐ 3= no change ☐ 4= don't know ☐ 5= flactuates ☐

26. If it has increased, what are the causes? 1= low rainfall ☐ 2= siltation ☐3= evaporation ☐ 4= irrigation ☐ 5= eutrophication ☐ 6= Others (specify)……………

27. If it has increased, how did you respond? Tick one or more 1= constructed dams ☐ 2= dug wells ☐ 3= sunk boreholes for humans ☐ 4= harvested rainwater ☐ 5= used off-farm sources

☐ 6= used electrolytes ☐ 7= fed water-rich plants ☐ 8= water-alleviating supplements/antioxidants ☐ 9= sold the animals ☐ 10= did nothing ☐

28. What are the water sources available for watering your sheep? (Tick one or more sources) 1= annual rivers ☐ 2= perennial rivers ☐ 3= dams ☐ 4= boreholes ☐ 5= wells ☐ 6= tap/piped water ☐

29. Have the water sources changed over the past 5 years? = decreased ☐ 2= increased ☐ 3= No change ☐ 4= don't know ☐ 5= flactuates

30. If they have decreased, how did you respond? 1= used off-farm sources ☐ 2= switched between sources ☐ 3= did nothing 4= Others (specify)………………………………

31. How far do your sheep travel in search of drinking water? 1= <1km ☐ 2= 2-5km ☐ 3= 5-10km 6 >10km ☐ 4= don't know ☐

32. Has the distance changed over the past 5 years?1= decreased ☐ 2= increased ☐ 3= No change ☐ 4= don't know ☐

33. If increased, how did you respond? 1= rain water harvesting ☐ 2= culled animals ☐3= off-farm sources ☐ Other (specify) …………………………………………………

34. Is the drinking water of your sheep clean? 1= Yes ☐ 2= No ☐

35. Has cleanliness changed over the past 5 years? 1= decreased ☐ 2= increased ☐ 3= no change ☐ 4= don't know ☐

36. If it has decreased, what are the causes? 1= dung ☐ 2= urine 3= mud/soil ☐ 5= don't know ☐ 6= dung/mud/soil ☐ 7= pollution

37. If it has decreased, how did you respond? 1= did nothing ☐ 2= used clean water ☐ 3= treated it ☐ 4= Other (specify) ……………………………………………………

38. Is the drinking water of your sheep safe? 1= Yes ☐ 2= No ☐

39. Has the safety changed over the past 5 years? 1= decreased ☐ 2= increased ☐ 3= no change ☐ 4= don't know ☐

40. If it has decreased, what are the causes? 1= microbes ☐ 2= parasites 3= salinity ☐ 4= chemicals ☐ 5= heavy metals ☐ 5= fertilisers ☐ 6= microbes/parasites ☐ 7= heavy metals/animal waste ☐ 8= stagnant water ☐

41. If it has decreased, how did you respond? 1= did nothing ☐ 2= used clean water ☐3= treated it ☐ 4= Other (specify) ……………………………………………………………

42. Has the temperature of drinking water for your sheep changed over the past 5 years? 1= decreased ☐ 2= increased ☐ 3= no change ☐ 4= don't know ☐ 5= seasonal changes ☐

43. If it has increased, what are the causes?1=high temperatures☐2=dry spells☐3=uncovered water sources☐4= don't know☐

44. If increased, how did you respond? 1= did nothing ☐ 2= provided shade on drinking water troughs ☐ 3= used cooler sources of water ☐

E. Effects of water scarcity on sheep production

a) Behaviour

45. On average, how much water does each animal in your flock drink per day?....................

46. Has drinking water intake for your sheep changed over the past 5 years? 1= decreased ☐ 2= increased ☐ 3= no change ☐ 4= don't know ☐ 5= seasonal changes ☐

47. If it has decreased, what might be the causes? 1= fouling by dung, mud and soil ☐ 2= salinity ☐ 3= warm water ☐ 4= don't know ☐ 5= weather changes ☐

48. If it has decreased, how did you respond? 1= used electrolytes ☐ 2= fed water-rich plants ☐ 3= water-alleviating supplements/antioxidants ☐ 4= used water-efficient breed ☐ 5= provided shade ☐ 6= did nothing 7= provided clean water ☐

49. Did you notice changes in behaviour of your sheep in response to scarcity of drinking water over the past 5 years? ☐ Yes ☐ No

50. If yes, what behavioural changes did you notice? (Tick) 1= grazing of animals during cool time of the day ☐ 2= increased drinking frequency ☐ 3= Increased restlessness ☐ 4= spent more time lying down during the day ☐ 5= panting ☐ 6= weight loss/ fertility loss/succumb to diseases ☐

51. How did you respond to the change/s in sheep behaviour? 1= used electrolytes ☐ 2= fed water-rich plants ☐ 3= water-alleviating supplements/antioxidants ☐ 4= used water-efficient breed ☐ 5= provided shade ☐ 6= used cooling systems ☐ 7= did nothing ☐ 8= provided water ☐

b) Growth performance and meat quality

52. On average, how much feed does each animal in your flock consume per day?................

53. Has scarcity of drinking water over the past 5 years affected feed consumption of your sheep? 1= decreased ☐ 2= increased ☐ 3= no change ☐ 4= don't know ☐

54. If it decreased feed intake, how did you respond? 1= used electrolytes ☐ 2= fed water-rich plants☐ 3= water-alleviating supplements/antioxidants ☐ 4= used water-efficient breed ☐ 5= did nothing ☐ 6= supplementary feeding ☐

55. On average, what is the body condition score of mature sheep in your flock? ? 1= poor ☐ 2= fair ☐ 3= good ☐ 4= very good ☐ 5= excellent ☐ 6= not sure

56. Has scarcity of drinking water over the past 5 years affected the body condition of your sheep? 1= decreased ☐ 2= increased ☐ 3= no change ☐ 4= don't know ☐ 5= changes seasonally ☐

57. If body condition decreased, how did you respond? 1= used electrolytes ☐ 2= fed water-rich plants ☐ 3= water-alleviating supplements/antioxidants ☐ 4= used water-efficient breed ☐ 5= did nothing ☐ 6= supplementary feeding

58. On average, what is the body weight of mature sheep in your flock? ……………………

59. Has scarcity of drinking water over the past 5 years affected the weight of your sheep?1= decreased ☐ 2= increased ☐ 3= no change ☐ 4= don't know

60. If it decreased weight, how did you respond?1= used electrolytes ☐ 2= fed water-rich plants ☐ 3= water-alleviating supplements/antioxidants ☐ 4= used water-efficient breed ☐ 5= did nothing ☐ 6= supplementary feeding ☐

61. How do you perceive carcass fat levels of your sheep? ? 1= poor ☐ 2= fair ☐ 3= good ☐ 4= very good ☐ 5= excellent ☐ 6= not sure

62. Has scarcity of drinking water over the past 5 years affected carcass fat levels of your sheep?1= decreased ☐ 2= increased ☐ 3=no change ☐ 4= don't know☐

63. If it has decreased carcass fat levels, how did you respond? 1= used electrolytes ☐ 2= fed water-rich plants ☐ 3= water-alleviating supplements/antioxidants ☐ 4= used water-efficient breed ☐ 5= did nothing ☐ 6= supplementary feeding ☐

64. How do you perceive the taste of your sheep meat? 1= poor ☐ 2= fair ☐ 3= good ☐ 4= very good ☐ 5= excellent ☐ 6= not sure ☐

65. Has scarcity of drinking water over the past 5 years affected the taste of your sheep meat? 1= decreased ☐ 2= increased ☐ 3= no change ☐ 4= don't know ☐

66. If it has decreased the meat taste, how did you respond? 1= used electrolytes ☐ 2= fed water-rich plants ☐ 3= water-alleviating supplements/antioxidants ☐ 4= used water-efficient breed ☐ 5= did nothing ☐ 6= Others (specify)……………….…………….

67. How do you perceive the tenderness of your sheep meat? ? 1= poor ☐ 2= fair ☐ 3= good ☐ 4= very good ☐ 5= excellent ☐ 6= not sure

68. Has scarcity of drinking water over the past 5 years affected the tenderness of your sheep meat? 1= decreased ☐ 2= increased ☐ 3= no change ☐ 4= don't know ☐

69. If it has decreased tenderness, how did you respond? 1= used electrolytes ☐ 2= fed water-rich plants ☐ 3= water-alleviating supplements/antioxidants ☐ 4= used water-efficient breed ☐ 5= did nothing ☐ 6= Others (specify)……………….……………

c) Reproduction

70. On average, how many lambs are born alive per ewe per year in your flock?..................

71. Has scarcity of drinking water over the past 5 years affected the number of lambs born per ewe per year in your flock? 1= decreased ☐ 2= increased ☐ 3= no change ☐ 4= don't know ☐

72. If it has decreased, how did you respond? 1= did nothing ☐ 2= supplemented/feed optimization ☐ 3= protected ewes from heat waves during breeding season ☐ 4= provided shade ☐ 5= used adapted breeds ☐ 6= combination ☐

73. On average, what is the lambing percentage of your flock?...

74. Has scarcity of drinking water over the past 5 years affected the lambing percentage of your flock? 1= decreased ☐ 2= increased ☐ 3= no change ☐ 4= don't know ☐

75. If it has decreased, how did you respond? 1= did nothing ☐ 2= kept lambs in dry and warm houses ☐ 3= combination ☐

76. On average, how many lambs are weaned per ewe per year in your flock?......................

77. Has scarcity of drinking water over the past 5 years affected the number of lambs weaned per ewe per year in your flock? 1= decreased ☐ 2= increased ☐ 3= no change ☐ 4= don't know ☐

78. If it has decreased, how did you respond? 1= did nothing ☐ 2= kept lambs in dry and warm houses ☐ 3= supplemented/feed optimization ☐ 4= provided shade

79. On average, how long is the lambing interval of ewes in your flock?...............................

80. Has scarcity of drinking water over the past 5 years affected the lambing interval of ewes in your flock? 1= decreased ☐ 2= increased ☐ 3= no change ☐ 4= don't know ☐

81. If it has increased, how did you respond? 1= did nothing ☐ 2= supplemented/feed optimization ☐ 3= protected ewes from heat waves during breeding season ☐ 4= provided shade ☐ 5= used adapted breeds ☐ 6= breeding improvement/vet assistance

82. What is the average age at first lambing in your flock?..

83. Has scarcity of drinking water over the past 5 years affected the age at first lambing of ewes in your flock? 1= decreased ☐ 2= increased ☐ 3= no change ☐ 4= don't know ☐

84. If it has increased, how did you respond? 1= did nothing ☐ 2= flush/supplement ☐ 3= separate rams

85. What is the average milk yield per ewe per day in your flock? ....

86. Has scarcity of drinking water over the past 5 years affected the milk yield of your flock? 1= decreased ☐ 2= increased ☐ 3= no change ☐ 4= don't know ☐ 5= seasonal changes ☐

87. If it has decreased, how did you respond? 1= did nothing ☐ 2= gave supplements 3= Other (specify)………………..…………………………………………………

d) Health

88. On average, how many sheep die in your flock per year?...

89. Has scarcity of drinking water over the past 5 years affected sheep mortality in your flock? 1= decreased ☐ 2= increased ☐ 3= no change ☐ 4= don't know ☐

90. If it has increased, how did you respond? 1= did nothing ☐ 2= sought vet assistance ☐ 3= medication ☐ 4= provided water ☐ 5= sought vet assistance/used traditional medicine ☐

91. What are the most common diseases that occur in your flock?1= pulpy kidney ☐ 2= blue tongue ☐ 3= gall sickness ☐ 4= malkop ☐ 5= tick borne diseases ☐ 6= sheep scab ☐ 7= abcess/sore mouth ☐ 8= sore eyes ☐ 9= rabbies ☐ 10= black leg ☐ 11= FMD ☐ 12= lumpy skin disease ☐ 13= diarrhoea/draught sickness ☐ 15= tuberculosis ☐ 16= back sit ☐ 17= swollen neck ☐ 18= liver fluke ☐ 19= blindness ☐

92. Has scarcity of drinking water over the past 5 years affected occurrence of disease in your flock? 1= decreased ☐ 2= increased ☐ 3= no change ☐ 4= don't know ☐

93. If it has increased disease occurrence, how did you respond? 1= did nothing ☐ 2= sought veterinary assistance ☐ 3= used disease resistant breed ☐ 4= medication ☐ 5= culled animals ☐

94. What are the most common external parasites that occur in your flock? 1= ticks ☐ 2= lice ☐ 3= mosquito ☐ 4= ticks and lice ☐ 5= ticks and mosquito ☐ 6= none ☐ 7= not sure ☐

95. Has scarcity of drinking water affected occurrence of external parasites on your flock over past 5 years? 1= decreased ☐ 2= increased ☐ 3= no change ☐ 4= don't know ☐

96. If it has increased external parasite occurrence, how did you respond? 1= did nothing ☐ 2= dipped animals ☐ 3= used traditional medicine ☐ 4= used parasite resistant breed ☐ 5= medication ☐

97. What are the most common internal parasites that occur in your flock?1= worms ☐ 2= fluke ☐ 3= none ☐ 4= not sure ☐

98. Has scarcity of drinking water over past 5 years affected occurrence of internal parasites on your flock? 1= decreased ☐ 2= increased ☐ 3= no change ☐ 4= don't know ☐

99. If it has increased internal parasite occurrence, how did you respond? 1= did nothing ☐ 2= dosed animals ☐ 3= used traditional medicine ☐ 4= used parasite resistant breed

e) Marketing

100. On average, how many sheep do you sell per year? ……………………………………

101. How has scarcity of drinking water over the past 5 years affected your sheep sales? 1= decreased ☐ 2= increased ☐ 3= no change ☐ 4= I don't know ☐

102. If it has decreased sheep sales, how did you respond? 1= did nothing ☐ 2= wait for good season ☐ 3= withhold sales ☐ 4= supplement ☐

103. What is your preferred marketing channel? 1= middlemen ☐ 2= sheep markets ☐ 3= abattoirs ☐ 4= farm-gate slaughters ☐ 5= other farmers ☐

104. Has scarcity of drinking water over the past 5 years affected your preferred channel? 1= yes ☐ 2= no ☐

105. If yes, how did you respond? 1= explored other channels ☐ 2= did nothing ☐ 3= withheld sales ☐

106. What is the average price for a live mature sheep in your area?.......................................

107. Has scarcity of drinking water over the past 5 years affected sheep prices in your flock? 1= increased ☐ 2= decreased ☐ 3= fluctuating ☐ 4= no change ☐ 5= don't know ☐

108. If it has decreased sheep prices, how did you respond? 1= did nothing ☐ 2= withheld sales ☐ 3= sell at reduced prices ☐

F. Barriers to water scarcity responses

109. What are the major factors limiting you from implementing drinking water scarcity response strategies for your sheep? Tick and rank (1= most important).

Barrier	Tick	Rank	Possible solution/s
Lack of information			
Lack of capital			
Lack of market access			
Lack of labour			
Lack of institutional support			
Lack of infrastructural support			
Lack of preparedness			
Lack of context specificity			

Appendix 2: Information on smallholder sheep farming areas where feedback meetings were held

Province	District	Municipality	Community	Dates	No. of farmers
Eastern Cape	O.R Tambo	Nyandeni	Libode	14/02/2022; 15/02/2022	24
			Nyandeni Centre	16/02/2022	8
	Chris Hani	Engcobo	Magqolweni; Nkondlo	17/02/2022	14; 12
			Lahlangubo, Upper cebe	18/02/2022	10;7
Northern Cape	Namakwa	Emthanjeni	De Aar	07/03/2022	10
			Hannover	08/03/2022	10
			Britstown	09/03/2022	07
	Pixley Ka Seme	Karoo-Hoogland	Fraserburg	10/03/2022	12
			Williston	11/03/2022	08
Western Cape	Central Karoo	Beaufort West	Laingsburg	11/04/2022	05
			Murraysburg	12/04/2022	12
			Beaufort West	13/04/2022	07
			Prince Albert	14/04/2022	05

Appendix 3: PowerPoints presentation made at farmer feedback meetings in the Cape Provinces (Find a separate attachment)

Appendix 4: Thesis abstracts of postgraduates in the project

Name of the student: Twanani Halimani

Supervisors: Prof C. Mapiye, Dr A.H Molotsi and Prof K. Dzama

Title of thesis: Smallholder sheep producers' perceptions of and response strategies to water scarcity in the Cape Provinces of South Africa

Abstract

Water scarcity is amongst the major challenges threatening smallholder sheep production in dryland areas. Farmer's perceptions and contextual factors are a prerequisite for effective policy development and optimisation of agricultural water resource management. Two-hundred and fifty-two structured questionnaires were administered to investigate the contextual factors that influence smallholder farmers' perceived effects of water scarcity on sheep production in the dry ecozones of the Cape provinces in South Africa and identify their local response strategies. Logit regression showed that participants in the semi-arid ecozone, extensive farmers, women, less educated respondents, owners of non-adapted breeds and livestock income earners had higher likelihood of perceiving negative effects of water scarcity on drinking water quality, sheep production and marketing than their counterparts. Farmers switched between water sources, provided supplementary feed and shade, used adapted breeds and alternative markets to manage the impact of water scarcity. Interventions to build resilience to water scarcity in the surveyed areas should target farmers with low adaptive capacity, particularly less educated women relying on livestock income and farming extensively with non-adapted breeds in the semi-arid ecozone.

Name of the student: Sandra Mupfiga

Supervisors: Prof C. Mapiye, Prof K. Dzama and Dr O. C. Chikwanha

Title of thesis: Water intake, nutrient utilization, and production efficiency of selected South African sheep breeds

Abstract

The main objective of the current study was to compare nutrient intake, water intake, nutrient digestibility, nitrogen and water balance, growth performance and carcass attributes of six South African sheep breeds kept under feedlot conditions. Fifty-seven, 4 to 5 months old wether lambs of pure indigenous (Pedi and Damara), indigenous composite (Meatmaster and Dorper) and exotic composite (Merino and Dohne Merino) wethers were used for the digestibility and growth trials. They were fed a pelleted total mixed ration containing 143.5 g crude protein (CP)/ kg DM and 10.29 MJ/ kg DM metabolisable energy. The wethers were adapted to the diet for 21 days, followed by 7 days of sample collection for digestibility trial and 42 days for growth trial. Breed had an influence on nutrient intake with Meatmaster having the highest dry matter (DM), organic matter (OM), CP, ash-free neutral detergent fibre (aNDFom) and ether extract (EE) intake followed by Damara, with Pedi having the least values ($P \leq 0.05$). Damara and Meatmaster had higher ($P \leq 0.05$) DM digestibility than the rest of the breeds. The aNDFom digestibility was in the following order: Dorper ≥ Merino ≥ Meatmaster ≥ Damara ≥ Dohne Merino ≥ Pedi. Damara had higher ($P \leq 0.05$) ether extract digestibility than the rest of the breeds. Meatmaster had the highest total N intake (feed + microbial N) and faecal N compared to other breeds ($P \leq 0.05$). Relative to other breeds, Meatmaster and Damara had higher ($P \leq 0.05$) N retention. Meatmaster, Dohne Merino, Damara and Dorper had higher ($P \leq 0.05$) positive water balance than Merino and Pedi. Average daily gain was highest for the Meatmaster and Damara, moderate for Dorper and Pedi and lowest for the Merino and Dohne Merino ($P \leq 0.05$). The feed conversion ratio was lowest for the Pedi with Dohne Merino having the highest ratio ($P \leq 0.05$). The Pedi drank the least amount of water while Meatmaster drank the highest ($P \leq 0.05$). Dohne Merino had the highest water to gain ratio while Pedi had the least ($P \leq 0.05$). Hot and cold carcass weights and dressing percentage were lower ($P \leq 0.05$) for the Damara and Pedi lambs compared to other breeds. Dohne Merino had the highest income over feed costs and Pedi had the least ($P \leq 0.05$). It was concluded that although Meatmaster had somewhat lower economic returns than Dohne Merino, the most common feedlot breed in South Africa, it had comparable water balance and carcass attributes and better nutrient intake, DM digestibility, N balance, growth rates and water utilisation efficiency making it a more suitable feedlot breed in water-scarce areas. Damara and Pedi had inferior carcass attributes and economic returns, but were the most water and feed efficient breeds, which could make them breeds of choice under extreme water scarcity conditions, particularly for small-scale feedlotters. The reported breed differences present an opportunity for producers to adopt breeds that suit their production systems and markets. Moreover, current findings provide opportunities for selective breeding and further development of feedlot sheep breeds to cope with water scarcity.

Name of the student: Bosede R Olagbegi

Supervisors: Prof C. Mapiye, Dr A.H Molotsi and Dr Chenai L. F. Katiyatiya

Title of thesis: Evaluation of meat physicochemical, fatty acid, volatile compound, shelf-life and sensory profiles of selected South African sheep breeds

Abstract

This study compared the physicochemical, shelf-life stability, fatty acid, volatile compound, as well as sensory profiles of meat from pure indigenous breeds (Pedi, n=8; Damara, n=10), indigenous composite breeds (Dorper, n=10; Meatmaster, n=9) and exotic composite breeds (Merino, n=10; Dohne Merino, n=10) fed under hot-dry feedlot conditions. Lambs were individually offered water and a pelleted total mixed ration (143.5 g crude protein (CP/kg DM and 10.29 MJ/ kg DM) for 42-days. The left and right longissimus thoracis et lumborum muscles were sampled for meat quality analysis. The study revealed that Dohne Merino had the highest intramuscular fat while Damara and Pedi had the least ($P \leq 0.05$). Meat lightness increased over time with Pedi having the highest values on day 7 of retail display followed by the Merinos ($P \leq 0.05$). On day 7, meat from the Merinos had the highest lipid oxidation values while Damara and Pedi had the lowest values ($P \leq 0.05$). The lowest meat protein oxidation values on day 7 were noted for the Meatmaster followed by Dohne Merino ($P \leq 0.05$). Rumenic acid (RA, c9,t11-18:2), linoleic acid (LA, 18:2n-6) and total omega (n)-6 polyunsaturated fatty acids (PUFA) proportions were highest in the Meatmaster and Pedi compared to other breeds ($P \leq 0.05$). Dohne Merino and Pedi had the greater ($P \leq 0.05$) α- linolenic acid (ALA, 18:3n-3), total n-3 PUFA and total PUFA than the other breeds. Regarding volatile compounds, Dohne Merino generally had the greatest concentrations of acids, alcohols and aldehydes, and lowest concentrations of esters ($P \leq 0.05$). Dohne Merino and Merino had slightly ($P \leq 0.05$) tender and juicier meat than Damara and Dorper. It was concluded that although pure indigenous breeds produced meat with comparable physicochemical, keeping and eating quality attributes to indigenous composite breeds and exotic composite breeds under hot-dry feedlot conditions, Pedi produced leaner meat with a more desirable fatty acid profile than the other breeds.

Name of the student: Nolutsha Pahlane

Supervisors: Dr A.H Molotsi and Prof C. Mapiye

Title of thesis: Comparative evaluation of South African sheep breeds tolerance to limited water availability of drinking water. Department of Animal Sciences, Stellenbosch University.

Abstract

Lamb production productivity and efficiency are critical factors in increasing sheep meat industry competitiveness. However, water scarcity is one factor hindering the industry's growth in South African drylands. Since sheep genetics determine meat production and quality, producers must intensify the use of local genetic resources to cope with water scarcity. Therefore, adopting breeds with low water requirements and high hydric stress tolerance in South Africa has become a high priority for the sheep industry, given the country's water challenges. Unfortunately, there is scant information on which South African sheep breeds are tolerant to water restriction under intensive (i.e. feedlot) production systems. A 42-day feedlot trial was, therefore, conducted to compare the effects of water restriction and breed (0, 10 and 20%) on the production performance and meat quality attributes of two indigenous (Pedi and Damara) and two composites (Dohne Merino and Meatmaster) South African sheep breeds. There was no interaction between water restriction × breed interaction for the investigated meat production and quality parameters. However, water restriction slightly reduced final live weight and increased meat redness without adversely influencing growth, carcass, and meat quality attributes. Overall, Meatmaster and Pedi had lower daily water intake than Dohne Merino. Meatmaster and Dohne Merino had superior carcass weights, income-over-feed-costs, lowest carcass pH, and the most tender meat relative to other breeds. Feed intake, average daily gain, and feed costs were higher in Damara than in Pedi and Meatmaster. Pedi had lighter and leaner carcasses and lower lamb meat, fat and rancid flavour scores than other breeds. It was concluded that water restriction up to 20% has no adverse effects on meat production and quality, and Meatmaster could be the ideal feedlot breed under water-scarce conditions.

NB: Thesis writing is on-going, and the student is expected to graduate in December 2023.

Name of the student: Muki A. Ditse

Supervisors: Prof U. Marume and Prof C. Mapiye

Title of thesis: Effects of water stress on physiological and blood metabolites parameters of South African sheep breeds. Department of Animal Sciences, North-West University

Abstract

The main objective of the proposed study was to determine the effects of water restriction on body weight changes, physiological parameters and welfare of different sheep breeds commonly raised in South Africa. Data analysis and thesis writing is in progress the student is expected to graduate in December 2023.