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Fatty acid profile, oxidative stability of lipids and sensory attributes of water restricted Xhosa goat meat supplemented with vitamin C

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ABSTRACT

Context. Water scarcity often accompanied by limited water intake (WI) in livestock may result in pre-slaughter stress, thereby affecting meat quality parameters. **Aims.** This study was conducted to determine the effect of vitamin C (VC) supplementations on fatty acid (FA), lipids oxidation and sensory attributes of *Longissimus lumborum* muscles of Xhosa goats subjected to different watering regimen. **Methods.** In total, 42 goats were randomly assigned into seven treatments: without water restriction, WR (W0, control); WR of 70% of *ad libitum* WI (W70); WR of 50% *ad libitum* WI (W50); WR of 70% of *ad libitum* WI + 3 g VC daily ($W70^{+}$); WR of 50% of *ad libitum* WI intake + 3 g VC daily ($W50^{+}$); WR of 70% of *ad libitum* WI + 3 g VC and extra 5 g VC given every 8 days ($W70^{++}$); WR of 50% of *ad libitum* WI + 3 g VC and extra 5 g VC given every 8 days ($W50^{++}$). The goats were fed for 75 days and killed following standard procedures. Bodyweight changes, thaw loss, ultimate pH (pH_u), thiobarbituric acid reactive substance (TBARS), moisture and fat content, sensory attributes and FA profile of the meat were evaluated. **Key results.** Results indicated that the decreased final weight in the untreated groups (W70 and W50) was reduced ($P > 0.05$) in the treated groups ($W70^{+}$, $W50^{+}$, $W70^{++}$, $W50^{++}$). The treatment effect was not significant ($P > 0.05$) on pH_u, thaw loss and TBARS values. The moisture and fat content in the water-restricted groups were lower ($P < 0.05$) than in W0. The meat sensory appearance was affected ($P < 0.05$) by WR. Regardless of VC concentration, vaccenic and docosahexaenoic acid increased ($P < 0.05$), while linolenic acid decreased as the WR levels increased. **Conclusions.** WR of 70% and 50% of *ad libitum* WI, with or without VC, did not negatively affect the meat's lipid oxidation and FA profile. **Implications.** Limited WI reduces body weight. However, a daily dose of VC could help reduce body weight loss during water scarcity.

Keywords: acceptability, antioxidants, lipid peroxidation, lipogenic enzymes, myofibrils, oxidative stress, pre-slaughter stress, water scarcity.

Introduction

Climate change and increasing water use due to rising populations have limited the amount of fresh water available to the populace, with a far-reaching effect in water-scarce and dry zones of the world (IPCC (Intergovernmental Panel on Climate Change) 2007; Akinmoladun *et al.* 2019). Livestock is the most affected as animal agriculture is known to be water-intensive (Gerbens-Leenes *et al.* 2013), and the availability of drinking water in sufficient amount is now a concern to farmers. Drinking water is limiting. Therefore, it is not surprising for livestock, especially ruminants in arid and water-limited or drought-hit regions, to trek long distances in search of water and pasture that is potentially richer in moisture content and nutritional value.

Small ruminants adaptively respond to limited water intake (WI) by reducing their feed intake to allow for low metabolic rate and less heat during the digestive process.

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This enables them to minimise dissipation due to evapotranspiration when the ambient temperature is high (Akinmoladun *et al.* 2019). When compared with other livestock species, ruminants are more resilient to suboptimal WI as losses >20% of body water can be tolerated due to rumen capacity to store water for later use (Jaber *et al.* 2004). However, water tolerance level varies among ruminant type and breeds (Shkolnik *et al.* 1980).

Despite this water-use efficiency, suboptimal WI in small ruminant affects animal performance and homeostasis, especially average daily intake and body weight (Mpendulo *et al.* 2020), while also promoting the development of oxidative stress (Akinmoladun *et al.* 2019). The excessive free radicals precipitated by oxidative stress not only affect productivity and overall performance of livestock but also impair cellular biomacromolecules (e.g. DNA, lipids and proteins) and mitochondrial integrity, thus accelerating lipid and protein peroxidation during ageing of meat and in processed meat products (Bekhit *et al.* 2013; Estévez 2015). Besides, there is a tendency for the quality of meat to be impaired by changing meat colour from red to dark red due to myofibres shrinkage, thus enhancing shrinkage loss and meat dryness (Jacob *et al.* 2006).

Acceptance of meat products by consumers depends primarily on meat flavour and tenderness (O'Quinn *et al.* 2018), and these characteristics may easily be affected by pre-slaughter stress. Antioxidant additives, such as vitamin C (VC), could be instrumental, when supplemented to live animal or added during meat processing, in combating the development of an oxidative environment, thus extending colour, lipid stability and prolonging shelf life (Rowe *et al.* 2004).

Although the National Research Council (NRC) (1981, 2007) did not describe clearly daily VC requirements for small ruminants because they have the potential to biosynthesise VC from glucose in the liver, plasma ascorbate concentrations were found to decrease following stressful and disease conditions (Ranjan *et al.* 2005). Positive outcomes have been reported in terms of improved feed efficiency and less bodyweight reduction following VC supplementations in heat-stressed poultry and swine (de Rodas *et al.* 1998; Sahin *et al.* 2003) and water-stressed Awassi ewes (Ghanem *et al.* 2008) respectively. It was hypothesised that supplemental VC would enhance a reducing environment by limiting the oxidation of lipids within the postmortem muscle and also improve the sensory attributes of the meat. Therefore, this study assessed the effect of VC supplementation to water-restricted Xhosa goats by evaluating its meat fatty acid (FA) profile, lipid oxidation and sensory attributes.

Materials and methods

Study site

The study was conducted at the University of Fort Hare farm situated in the False Thornveld of the Eastern Cape. It has a geographical coordinate of 32.8′S and 26.9′E. The summer months (November–March) are characterised by a warm climate, with most of the annual rainfall (average of 480 mm) being received during this period. The mean average minimum and maximum temperatures during the study period (January–March 2019) were 18.03°C and 27.04°C respectively, and relative humidity of 65.71%.

Animal management and treatment designs

Forty-two female goats (Xhosa ear-lope breed), with an initial mean body weight of 15.92 ± 2.12 kg and of approximately 12 months of age, were randomly assigned to seven groups consisting of six goats each, as follows: without water restriction, WR (W0, control); WR of 70% of *ad libitum* WI (W70); WR of 50% *ad libitum* WI (W50); WR of 70% of *ad libitum* WI + 3 g VC daily ($W70^{+}$); WR 50% of *ad libitum* WI + 3 g VC daily ($W50^{+}$); WR of 70% of *ad libitum* WI + 3 g VC and extra 5 g VC given every 8 days ($W70^{++}$); WR of 50% of *ad libitum* WI + 3 g VC and extra 5 g VC given every 8 days ($W50^{++}$).

Body weight and body condition scores were balanced for all groups. They were thereafter acclimatised to the diets and housing conditions for 14 days before collecting data for 75 days. The goats were individually kept in pens, with a feeder and water trough. Throughout the whole experimental period, a hygienic environment was maintained and regular observation of each animal's physical conditions.

Feed offered to the animals was the same and presented as a total mixed ration (TMR, 70% Lucerne hay and 30% concentrate) based on 4% of their body weight dry matter (DM). Diet was formulated to satisfy the requirements for growing goats (National Research Council (NRC) 1981). The nutrient composition of the TMR was determined from the diet mixture samples taken at the end of the experiment (Table 1). The diet mixture was analysed for DM (method number 934.01), crude protein (method number 954.01), ether extract (method number 920.39), organic matter (method number 925.05) and mineral content (method number 942.05) of AOAC (2000).

The L-ascorbic acid (VC) used as a supplement was sourced from Minema Chemical Stores, Gauteng, South Africa. All animals receiving VC supplementation were subjected to a 6-day preparation period (coinciding with the last 6 days during the adaptation period), during which they were orally supplemented with 10 g VC/50 mL water per animal. This was undertaken to ensure that the animals were at the same VC status (Ghanem *et al.* 2008).

Table 1. Ingredients and composition of standard diet (g/kg DM).

Ingredient	Quantity
Lucerne	700
Maize gluten	166.3
Sunflower husk	127.3
Limestone	2.1
MCDP	2.3
Salt	1.5
Premix[A]	0.6
Calculated composition	
Organic matter	889.5
Crude protein	216.7
Ether extract	17.5
Crude fibre	215.3
Nitrogen free extract	440
Phosphorus	3.8
Calcium	15.7
Magnesium	6.0
Potassium	8.3
Sodium (mg/kg)	2263
Copper (mg/kg)	41
Iron (mg/kg)	116
Manganese (mg/kg)	38
Zinc (mg/kg)	18

[A]Ca – 220 g/kg; P – 55 g/kg; Mg – 35 g/kg; S – 22 g/kg; Cl – 105 g/kg; Na – 70 g/kg; Mn – 1500 mg/kg; Fe – 500 mg/kg; Zn – 1550 mg/kg; Cu – 440 mg/kg; Co – 50 mg/kg; I – 40 mg/kg; Se – 20 mg/kg.

The 3 g/day VC dose was selected on the basis of previous findings on the effectiveness and higher bioavailability at lower doses (Tyler and Cummins 2003; Jaber *et al.* 2011). Also, bioavailability of oral VC can be increased with multiple dosing compared with single dosing in animals (Hidiroglou *et al.* 1997). Hence, the extra 5 g VC was given to the goats every 8 days.

Feeding and watering activities

Feed was offered two times a day, at 0900 hours and 1600 hours, in equal proportions. Daily intake was determined by subtracting the leftovers collected from the weighted feed given the previous day.

WR percentages for experimental groups were calculated on the basis of the control group's daily *ad libitum* intake. Water was provided in containers of known volume and was topped up once a day. The control group receives water twice daily at 0800 hours and 1500 hours to determine the quantity of water ingested. Total WI was calculated as the difference between the amounts offered and leftovers and rebating loss of water due to evaporation. Water loss due to evaporation was calculated by putting buckets filled with water at focal points in the pen to estimate loss due to evaporation. W70 and W50 groups did receive drinking water daily at 70% and 50% of the intake recorded in the control group (W0) respectively.

Slaughter procedures

The animals' slaughtering and dressing were conducted at a small through-put abattoir in Adelaide (63.1 km from the University of Fort Hare), under Nxuba Local Municipality, following standard procedures. Carcasses were split, weighed and then chilled (0–4°C), before being processed the day after slaughter. Thereafter, samples (100 mm thick piece) of *Longissimus thoracis* et *lumborum* (LTL) of the right side were collected from the 10th rib in the right direction of the rump and the right LTL's posterior side. Subsequently, the connective tissue and subcutaneous fat were removed and vacuum-packaged at 0–4°C for chemical composition, lipid oxidation and FA analysis.

Thaw loss and ultimate pH determination

The pH was measured in the LTL muscle between the 12th and 13th ribs, 24 h post-slaughter. Samples for thaw loss were weighed and frozen at −20°C for 24 h. Thereafter, the frozen samples were thawed at 4°C for 12 h and reweighed. Thaw loss was calculated as:

$$\text{Thaw loss} = \left[\frac{\text{weight before thaw} - \text{weight after thaw}}{\text{weight before thaw}}\right] \times 100$$

Determination of lipid oxidation (TBARS)

The acid-precipitation technique of thiobarbituric acid reactive substance (TBARS) (with slight modification) was used to determine lipid oxidation in the meat samples. Briefly, 2 g of sample was weighed (in triplicate) into 50 mL tubes and homogenised (Ultraturax) for 20 s after the addition of 6.25 mL each of trichloroacetic acid (0.001 M) and distilled water (dH_2O). The homogenate was filtered using a Whatman no1 filter paper. A standard curve was constructed (in triplicate) using 0, 5, 10 and 20 μL 1,1,3,3-tetramethoxypropane (0.001 M) in 1 mL of dH_2O. There were three tubes allocated for each sample, and 1 mL of the filtrate was added to each tube. To each prepared standard and two tubes of filtrate samples, 1 mL of thiobarbituric acid was added, while 1 mL of dH_2O was added to the third filtrate sample tube to act as a turbidity blank at 70°C for 1 h. Thereafter, samples were allowed to cool, and the absorbance was read at 530 nm (Spectrostar Nano, BMG Labtech, Ortenberg, Germany). TBARS, expressed as mg of malondialdehyde (MDA)/kg meat, was calculated as:

$$\text{TBARS (mg MDA/kg meat)} = \frac{\text{absorbance} \times \text{molar mass of MDA} \times \text{volume of extract} \times \text{dilution factor}}{\text{sample mass} \times \text{slope of standard curve}}$$

Sensory characteristics

To assess the meat sensory attributes, some pieces (approximately 3 cm^3) were cut (per treatment group) from the LTL muscle, wrapped with aluminium foil and cooked in an oven (pre-heated to 200°C) using a baking pan. Cooking was deemed complete when the geometric centre of the samples reached 75°C. Thereafter, samples were labelled and the sequence of serving randomised. Sensory attributes such as colour, texture, taste–odour and acceptability were considered when evaluating the samples. Each sample was evaluated by 12 panellists using a nine-point hedonic scale. The nine-point descriptive scales used in the evaluation were designed as follows: colour (1 = extremely light red to 9 = dark brown), taste–aroma (1 = extremely bland to 9 = extremely intense); appearance (1 = dislike extremely to 9 = like extremely), texture (1 = extremely soft to 9 = extremely hard) and acceptability (1 = dislike extremely to 9 = like extremely; Pena *et al.* 2009). The panellists used had over 5 years of experience in sensory evaluation.

Determination of FA profile

Quantitative extraction of total muscle lipid from LTL samples (Folch *et al.* 1957) was performed using a mixture of methanol and chloroform (ratio of 1:2), followed by the addition of butylated hydroxytoluene (concentration of 0.001%). The fat extract was dried overnight with the aid of a rotary evaporator and phosphorus pentoxide (moisture adsorbent) under a vacuum oven (50°C). The extracted fat was gravically used to quantify the total extractable intramuscular (expressed as per cent fat (w/w) per 100 g tissue). To determine fat-free DM (FFDM) content, the residue was weighed on a pre-weighed filter paper after drying and expressed as per cent FFDM (w/w) per 100 g tissue after calculating weight differences. To determine the moisture content (expressed as per cent moisture (w/w) per 100 g tissue), per cent FFDM and lipid were subtracted from 100. The extracted fat was kept in a polytop (glass vial, with push-in top) beneath nitrogen blanket and frozen (−20°C) pending FA analyses.

To avoid conjugated linoleic acid (CLA) isomerisation, muscle lipid aliquot (±30 mg) was converted to methyl esters by base-catalysed transesterification for 2 h at 30°C with sodium methoxide (0.5 M solution in anhydrous methanol; Park *et al.* 2001; Kramer *et al.* 2002; Alfaia *et al.* 2007). Thereafter, the FA methyl esters (FAMEs) from the muscle were quantified using a Varian 430 flame ionisation gas chromatography, with a fused silica capillary column, Chrompack CPSIL 88 (100 m length, 0.25 mm ID, 0.2 μM film thicknesses). The analysis was performed using an initial isothermic period (40°C for 2 min) while the temperature increased to 230°C at a rate of 4°C/min and was maintained at this temperature for 10 min. FAMEs in *n*-hexane (1 μL) were injected into the column using a Varian CP 8400 Autosampler. The injection port and detector were maintained at 250°C with hydrogen (45 psi) and nitrogen functioning as the carrier and makeup gas. Galaxy Chromatography Data System Software recorded the chromatograms reading.

Retention times of FAME peaks from samples were compared to standards obtained from Supelco (Supelco 37 Component Fame Mix 47885-U, Sigma–Aldrich Aston Manor, Pretoria, South Africa) to identify FAME samples. CLA standards were obtained from Matreya Inc. (Pleasant Gap, USA). These standards included: *cis*-9, *trans*-11 and *trans*-10, *cis*-12-18:2 isomers.

FAs were expressed as the proportion of each FA to all FAs present in the sample. FA data were used to calculate the following ratios of FAs: total saturated FAs (SFAs); total monounsaturated FAs (MUFAs); total polyunsaturaed FAs (PUFAs); PUFA:SFA; Δ^9 desaturase index (C18:1c9:C18:0); total omega-6 (*n*-6); total omega-3 (*n*-3); the ratio of omega-6 (*n*-6):omega-3 (*n*-3) FAs. Atherogenicity index (AI) was calculated as AI = (C12:0 + 4 × C14:0 + C16:0) / (MUFA + PUFA) (Chilliard *et al.* 2003).

Statistical analysis

Data obtained were analysed using the general linear model procedure of SAS Institute Inc. (2013). The sensory scores were transformed using the arcsine transformation to achieve normality and reported as back-transformed means. The linear model was

$$Y_{ij} = \mu + B_i + \varepsilon_{ij},$$

where Y_{ij} is the dependent variable, μ is the overall mean, B_i is the effect of diet and ε_{ij} is the random error.

Where differences exist, the means were separated using Fisher's least significance difference method of SAS, with a significance level of $P = 0.05$.

Ethical clearance

The experimental protocol described in this study was approved by the Research and Ethics Committee of the University of Fort Hare, South Africa (Ref. No: MUC011SAKI01).

Results

Performance characteristics

The performance characteristics of water-restricted Xhosa goats supplemented with VC are shown in Table 2. A higher decrease ($P > 0.05$) in final weight (FW) was observed in the W70 and W50 groups. However, the FW decrease was less in the treated groups ($W70^{+}$, $W50^{+}$, $W70^{++}$, $W50^{++}$). The body weight gain (loss) was affected ($P < 0.05$) by the WR level. Group W50 had the highest body weight loss. In the treated groups ($W70^{+}$, $W50^{+}$, $W70^{+}$+ and $W50^{++}$), body weight loss was lessened compared with the untreated groups (W70 and W50). The amount of water ingested decreased ($P < 0.05$) to depict the watering regimen adopted. All water-restricted groups had a reduced ($P < 0.05$) DM intake compared with the control. When water-restricted groups were compared, goats under $W70^{++}$ and $W50^{++}$ groups had the highest ($P < 0.05$) DM intake, followed by $W70^{+}$ and $W50^{+}$, and the lowest values recorded were in W70 and W50 groups.

Oxidative stability, ultimate pH, thaw loss and proximate

Lipid oxidation values (as determined by TBARS), ultimate pH (pH_u) and thaw loss are shown in Table 3. Effect of WR levels and VC supplementation were not significant ($P > 0.05$) on TBARS (mg/kg), ultimate pH ($pH_{24\ h}$) and thaw loss. The moisture and fat content of the entire water-restricted groups were lower ($P < 0.05$) than those of the control.

Sensory attributes

The effect of different watering treatments on the sensory attributes of the *L. lumborum* of Xhosa goat is shown in Table 4. Regardless of VC supplementation, the colour, odour and texture were not affected (P SE > 0.05) by the WR level. However, the sensory meat appearance was affected ($P < 0.05$) by the watering treatments.

Fatty acids

The FA composition in the *L. lumborum* muscle of Xhosa goats subjected to different watering treatments is shown in Table 5. The WR levels and VC supplementation had no effect ($P > 0.05$) on myristic (C14:0), pentadecylic (15:0), palmitic (C16:0), heptadecenoic (C17:1c1), stearic (C18:0), oleic (C18:1c9) and linoleic (C18:2td,12 (*n*-6)). Regardless of VC supplementation and/or concentration, proportions of vaccenic (C18:1t11), docosahexaenoic (C22:6c4,7,10,13, 16,19 (*n*-3)) increased ($P < 0.05$) while palmitoleic (C16:1c9), α-linolenic (C18:3c9,12,15 (*n*-3)), CLA (C18:2c9,

Table 2. Performance of water-restricted Xhosa goats supplemented with VC.

Variable	W0	W70	W50	$W70^{+}$	$W50^{+}$	$W70^{++}$	$W50^{++}$	s.e.m.	*P*-value
IW (kg)	15.7	15.6	16.2	16.2	15.8	15.9	16.1	2.24	0.42
FW (kg)	17.9	13.9	13.7	14.9	14.5	14.3	14.4	2.07	0.07
Gain (kg)	2.2a	−1.7bc	−2.5c	−1.3b	−1.3b	−1.6bc	−1.7bc	0.37	0.02
ADG (g/day)	29.8a	−22.7bc	−32.9c	−16.9b	−17.3b	−21.3bc	−23.1bc	4.87	0.02
DMI (kg/day)	0.6a	0.4c	0.3e	0.4bc	0.3de	0.4b	0.4d	0.01	<0.01
WI (kg)	92.5a	62.4b	45.6c	62.4b	45.6c	62.4b	45.6c	4.12	<0.01
WI:DMI	2.3a	2.3a	1.9b	2.2a	1.8b	2.2a	1.8b	0.09	0.01

Means with different letters across the row are significantly different ($P < 0.05$); $^{+}$, 3 g VC daily; $^{++}$, 3 g VC daily + extra 5 g VC every 8th day.
ADG, average daily gain; DMI, total dry matter intake; s.e.m., standard error of the mean; WI, water intake; WR, water restriction.

Table 3. Effect of different watering treatments on malonaldehyde content, ultimate pH, thaw loss and proximate of the *Longissimus lumborum* of Xhosa goats.

Variable	W0	W70	W50	$W70^{+}$	$W50^{+}$	$W70^{++}$	$W50^{++}$	s.e.m.	*P*-value
TBARS (mg/kg)	0.7	0.8	0.8	0.7	0.7	0.7	0.8	0.08	0.10
$pH_{24\ h}$	5.9	5.9	5.9	5.9	5.9	5.9	5.9	0.01	0.09
Thaw loss (%)	9.9	9.6	8.7	9.8	8.8	9.9	9.0	0.43	0.07
Moisture (%)	79.1a	76.4b	75.4b	77.9ab	75.9b	78.10b	77.7ab	1.23	0.02
Fat (%)	2.1a	1.4b	1.3b	1.4b	1.4b	1.5b	1.5b	0.16	<0.01
FFDM (%)	18.7c	22.3a	23.2a	20.7b	22.6a	20.4b	20.8b	0.58	0.04

Means with different letters across the row are significantly different ($P < 0.05$); $^{+}$, 3 g VC daily; $^{++}$, 3 g VC daily + extra 5 g VC every 8th day.
s.e.m., standard error of the mean; FFDM, fat-free dry matter; TBARS, thiobarbituric acid reactive substance.

Table 4. Average points for the effect of different watering treatments on the sensory characteristics of the *Longissimus lumborum* of Xhosa goats.

Variable	W0	W70	W50	W70^{+}	W50^{+}	W70^{++}	W50^{++}	s.e.m.	*P*-value
Colour	6.4	6.6	6.8	6.6	6.8	7.0	6.4	0.49	0.16
Taste + aroma	6.6	6.8	6.8	6.8	6.4	6.4	6.6	0.34	0.11
Appearance	6.6a	6.0abc	5.6c	6.4ab	5.8bc	6.0abc	6.0abc	0.38	0.01
Texture	5.4	5.5	5.6	5.4	5.6	5.6	5.6	0.50	0.12
Acceptability	6.4	6.0	5.6	5.8	5.6	5.8	5.6	0.46	0.08

Means with different letters across the row are significantly different ($P < 0.05$); $^{+}$, 3 g VC daily; $^{++}$, 3 g VC daily + extra 5 g VC every 8th day.
s.e.m., standard error of the mean.

t11 (*n*-6)) and docosahexaenoic (C22:6c4,7,10,13,16,19 (*n*-3)) decreased with increasing levels of WR. The total FA, sums and ratios of FAs, *n*-6, *n*-3, AI and desaturase indices were not affected ($P > 0.05$) by WR and VC. VC supplementation, regardless of dose, increased ($P < 0.05$) the sum of MUFAs in the water-restricted treated groups.

Discussion

Regardless of the restriction in water availability, the temperature recorded during the study period does not seem very physiologically challenging, especially for a local breed adapted to the region. In ruminants, body water is closely associated with body weight, and suboptimum intake usually results in a body weight fall (Akinmoladun *et al.* 2019). The decreased body weight in the water-restricted groups could be attributed to reduced water and DMI. Usually, feed ingestion and water consumption are positively correlated (Thang *et al.* 2012). Similar depressions in DM intake induced by WR or deprivation have been reported (Maloiy *et al.* 2008; Casamassima *et al.* 2016). However, there was less body weight loss in the VC-treated groups. A probable reason could be improved feed intake in the treated groups compared with the untreated water-restricted groups. In a similar study, water-deprived Awassi ewes had their weight improved from 48.75 kg (restricted group) to 55.5 kg (treated group) following a daily dose of 2.5 g/day of ascorbic acid (Ghanem *et al.* 2008). This improvement may be due to the ability of ascorbic acid to effectively scavenge free radicals and reactive oxygen species generated following increased lipid mobilisation and metabolic stress induced by negative energy balance in water-limited animals (Akinmoladun *et al.* 2020). However, DM intake depression was reduced in the VC-treated groups.

Non-microbial quality degradation in meat or its products, specifically under pro-oxidative conditions, is mainly due to lipid oxidation (Bekhit *et al.* 2013). However, the TBARS values have now been widely accepted as an indicator of oxidation of muscle lipids at the biochemical level (Lorenzo and Gómez 2012). Regardless of VC concentrations and supplementation, the TBARS values were not affected by the WR level. These values were consistent with the results for PUFA in the *L. lumborum* muscle in the present study, thus justifying the similarity in the TBARS values. The oxidative stability of lipid in meat is dependent on the equilibrium between pro-oxidants (including the concentrations of reactive oxygen species, PUFA and haem pigment) and antioxidants (e.g. some carotenoids and α-tocopherol; Bekhit *et al.* 2013). The higher the level of unsaturated lipids in meat compared compared with the saturated, the more prone is the meat to lipid oxidation. In a similar study, the oxidative stability of grass-fed ground beef treated with VC was not affected (Realini *et al.* 2004). Also, studies have reported lipid oxidation to be unaffected by stress induced by slaughtering methods in rabbits (Nakyinsige 2014) and lambs (Linares *et al.* 2007). Adverse pre-slaughter stress influences meat quality characteristics such as ultimate pH, tenderness and thaw loss (Mouzo *et al.* 2020). Regardless of VC supplementation, the ultimate pH_u and thaw loss were not affected by the WR level. In a similar study, transportation-induced pre-slaughter stress did not affect the pH_u and thaw loss in goats (Kannan *et al.* 2003). In a study conducted on lambs and kids subjected to pre-slaughter stress and VC supplementation, Saribey and Karaca (2019) reported that the pH_u in lambs was not affected by the treatment effect while kids treated with VC had a lower pH_u than did those in the untreated group. Goats are more sensitive to peri-mortem stress, consequently affecting the conversion process of muscle to meat, leading to a pH_u range between 5.8 and 6.2 (Simela *et al.* 2004; Webb *et al.* 2005).

Variability in the eating quality of meat has been attributed to the ultimate $pH_{24\,h}$, with a higher meat pH producing higher thaw and cooking losses and reduced shelf life (Ekiz *et al.* 2012). However, the ultimate pH_u range reported in the present study is between 5.87 and 5.90 (<6.0) and is low enough to discourage high thaw loss. The water content of meat is important in food analysis due to its influence on carcass dressing, storage, packaging and processing (Jimenez Colmenero 1996). The similarity in WI between those watered with W50 and W70 (treated and untreated) of *ad libitum* intake evinced goats' adaptive nature during water scarcity, an attribute linked to the rumen and its ability to conserve water during shortfalls (Silanikove 2000).

Table 5. Fatty acid composition in *Longissimus lumborum* muscle (% of total fatty acid) of Xhosa goats subjected to different watering treatments.

Variable	W0	W70	W50	W70^{+}	W50^{+}	W70^{++}	W50^{++}	s.e.m.	*P*-value
Saturated (SFA)									
Myristic (C14:0)	2.20	1.84	1.99	2.30	1.75	1.81	1.38	0.51	0.16
Pentadecylic (15:0)	0.40	0.38	0.40	0.42	0.35	0.35	0.32	0.05	0.27
Palmitic (C16:0)	26.58	25.54	25.41	27.23	25.57	25.63	25.44	1.19	0.07
Margaric (C17:0)	1.45a	1.39b	1.33c	1.41ab	1.21d	1.46a	1.15e	0.02	<0.01
Stearic (C18:0)	19.83	20.06	19.45	19.39	20.98	20.08	20.89	0.56	0.10
Nonoadecanoic (C19:0)	0.06	0.08	0.07	0.06	0.08	0.08	0.08	0.01	0.18
Arachidic (C20:0)	0.08	0.09	0.08	0.08	0.08	0.09	0.08	0.01	0.07
Monounsaturated (MUFA)									
Palmitoleic (C16:1c9)	0.82c	0.75c	0.79c	1.62a	1.27b	0.86c	0.84c	0.15	<0.01
Heptadecenoic (C17:1c1)	0.16	0.18	0.18	0.16	0.17	0.17	0.16	0.02	0.07
Oleic (C18:1c9)	33.32	32.98	32.07	33.84	32.60	35.67	35.74	1.71	0.56
Vaccenic (C18:1t11)	1.55c	1.77b	2.13a	1.55c	1.72b	1.70bc	1.61bc	0.09	<0.01
Polyunsaturated (PUFA)									
Linoleic (C18:2*n*-6)	7.00	7.58	6.99	6.64	6.45	6.64	6.56	0.86	0.08
Linolenic (C18:3*n*-3)	1.90a	1.65b	1.57b	1.55b	1.49b	2.00a	1.49b	0.09	<0.01
CLA[A]	0.08	0.08	0.07	0.09	0.08	0.08	0.06	0.02	0.02
EDA[B]	0.06	0.06	0.05	0.05	0.05	0.05	0.05	0.01	0.71
Arachidonic (C20:4*n*-6)	7.00	8.96	8.55	7.56	7.20	8.01	7.97	1.88	0.10
EPA[C] (C20:5*n*-3)	2.70	3.31	3.70	2.13	2.65	2.88	3.12	0.39	0.19
DPA[D] (C22:4*n*-6)	2.71	2.72	2.64	2.10	2.29	2.50	2.54	0.34	0.12
DHA[E] (C22:6*n*-3)	0.62b	0.74b	0.93a	0.57b	0.58b	0.96a	1.01a	0.09	<0.01
Sums and ratios									
ΣSFA	48.15	48.92	50.69	48.61	48.63	49.05	49.42	1.73	0.27
ΣMUFA	26.93cd	26.97cd	25.60d	32.82a	31.09ab	29.08bc	28.84bc	1.69	0.01
ΣPUFA	22.38	22.88	25.48	23.57	24.86	23.32	21.74	3.37	0.09
Σ*n*-6	14.09	14.71	13.75	12.79	11.38	14.81	13.65	2.61	0.09
Σ*n*-3	8.29	8.18	7.73	7.17	7.07	8.51	8.08	0.88	0.13
PUFA:SFA	0.47	0.46	0.50	0.48	0.50	0.47	0.44	0.09	0.09
PUFA:MUFA	0.82	0.85	0.98	0.72	0.81	0.80	0.75	0.20	0.06
Σ*n*-6:Σ*n*-3	1.67	1.80	1.79	1.78	1.60	1.74	1.69	0.18	0.16
AI[F]	0.70	0.63	0.68	0.71	0.62	0.61	0.61	0.09	0.21
DI[G]	1.18	0.94	1.14	1.14	1.17	1.31	1.22	0.19	0.77

Means with different letters across the row are significantly different ($P < 0.05$); $^{+}$, 3 g VC daily; $^{++}$, 3 g VC daily + extra 5 g VC every 8th day.
[A]Conjugated linolenic acid (C18:2c9,t11 (*n*-6)).
[B]Eicosadienoic acid (C20:2c11,14 (*n*-6)).
[C]Eicosapentanoic acid.
[D]Docopentanoic acid.
[E]Docosahexanoic acid.
[F]Atherogenecity index.
[G]Desaturase index.
s.e.m., standard error of mean; WR, water restriction.

Nonetheless, the mean value of 76.9% in all of the water-restricted groups in this study exceeded 75% and 73% in sheep (Madruga *et al.* 2008) and water-restricted Brazilian goats (dos Santos *et al.* 2019) respectively. The low crude fat in the water-restricted groups compared with the control could be attributed to fat mobilisation from adipose tissues in response to reduced feed intake induced by limited WI. According to Jaber *et al.* (2011), fat is mobilised during

water scarcity and/or suboptimum WI to meet the animal's energy requirements in response to decreased feed intake and weight loss.

One of the meat quality parameters that interest consumers and producers and retailers are the meat sensory attributes. Aroma or flavour (aroma + taste) are usually affected by the age of the animal and the type and nature of feed offered, and those differences may influence consumer acceptability (Font *et al.* 2009; Watkins *et al.* 2013). However, most sensorial parameters assessed (colour, odour, acceptability and texture) in this study were not affected by the pre-slaughter stress and DM intake differentials induced by limited WI. This lends credence to the report of Miranda-de la Lama *et al.* (2012) that a much higher stress level than the one that can affect physicochemical and meat quality parameters is required to induce significant changes to sensory attributes. The effect of the WR level caused substantial changes in the appearance of the meat. The panellist observed that the appearance scores for all the water-restricted groups oscillated between 'like slightly' (score 6) to 'neither like nor dislike' (score 5) and with a progressive tendency to dislike meat from an animal with higher water limitations. This may probably be attributed to the WI differences and, consequently, the meat water content. Moisture retention of fresh meat is arguably an essential quality characteristic of raw products. Although the effect of the WR level was not significant on thaw loss, the values obtained linearly decreased as the WR level increased. Water is usually held in myofibrils in the space between filaments, bounding small protein proportions by electrostatic attraction (Ponnampalam *et al.* 2017). Meat with low moisture, probably due to limited WI, affected its appearance and consumers' dislike.

The FA profile of goat meat, compared with other types of red meat, showed the existence of essential FAs (low SFAs), high concentrations of oleic acid, and low concentrations of myristic, lauric and palmitic acids (Lopes *et al.* 2014). This is seen to be highly beneficial to human health if consumed. Regardless of the WR level and VC supplementation, the most abundant FAs were the oleic (18:1c9), palmitic (C16:0) and stearic (C18:0) acids, in that order, and their concentrations were not affected by the quantity of water ingested. Similar studies have reported oleic acid (C18:1c9) concentrations to be the most abundant in the muscle of sheep, goats and cattle (Oliveira *et al.* 2012; Roy *et al.* 2013; Ferreira *et al.* 2014). Regardless of VC supplementation, the observed similar concentrations of oleic acid in the water-restricted and control groups are suggestive that the conversion (*de novo*) of C18:0 to C18:1c9 by Δ^9 desaturase enzyme (Adeyemi *et al.* 2015) was not compromised by limited WI. Oleic acid, the most abundant (about 30–43%) of the MUFAs, is hypocholesterolemic in its *cis* form and can be influenced by the dietary type and the amount of voluntary feed intake (Melton *et al.* 1982; Adeyemi *et al.* 2015). In this study, the percentage of oleic acid was the highest of all the MUFAs and with a similar range (32.07–35.74%).

The non-significant effect of the medium-chain FAs (myristic and palmitic acids) in response to the WR level could be that their synthesis or incorporation from adipose tissue and/or diet by lipogenic enzymes were not inhibited (Kim *et al.* 2007). A similar outcome was reported by dos Santos *et al.* (2019) in feedlot lamb subjected to a different watering period of 24, 48 and 72 h. Myristic and palmitic acids are considered hypercholesterolemic, being capable of raising the concentration of low-density lipoprotein. In contrast, stearic acid (long-chain FAs) are neutral for plasma cholesterol (Scollan *et al.* 2001).

The concentration of vaccenic acid (C18:1t11) increased with an increased WR level, especially in the W50 (untreated) group. Both vaccenic acid and CLA are intermediate products of ruminal biohydrogenation of unsaturated FAs to SFAs from the diet (Kim *et al.* 2007). The reduction in DMI induced by suboptimal WI may affect the bacteria population responsible for the complete conversion of unsaturated FAs to SFAs, thereby accumulating higher concentrations of vaccenic acid with the WR level. Vaccenic acid (C18:1t11) is subsequently absorbed from the small intestine and deposited in the muscle tissue (Adeyemi *et al.* 2015).

On the basis of studies, CLA is produced from Δ^9 desaturations of vaccenic acid (C18:1t11) in adipose tissue (Adeyemi *et al.* 2015). The progressive increase in vaccenic acid with respect to the WR level was expected to increase CLA. However, the CLA values obtained in this study were not affected by the WR level and VC supplementation. Contrarily, dos Santos *et al.* (2019) reported a decreasing trend in CLA of *L. lumborum* of feedlot lambs subjected to WR. The observed differences may be due to an imbalance in the mRNA synthesis of Δ^9 desaturase enzyme (Baumgard *et al.* 2001), induced by the reduced intake of water and feed, thereby affecting the concentrations of CLA in the muscle of animals with less water.

Both eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA) are important precursors of eicosanoids, modulating several cellular functions and integrity, especially the cardiovascular system. DHA increased with an increased WR level while EPA remained unaffected. EPA is formed by desaturation and stretching of alpha-linolenic acid (Calder 2013); hence, the non-significant effect to the WR level may be that the synthesis of Δ^6 desaturase and elongases enzymes that are required for the conversion of α-linolenic acid into its long derivate were not compromised (Pawlosky *et al.* 2003). While, in contrast, the water and feed intake differentials may have induced linolenic acid conversion into DHA by increasing the synthesis of the required enzymes. DHA is vital for the proper functioning of the cell membrane and is also involved in retina and brain development (Ramakrishnan *et al.* 2010).

The effect of WI differentials with or without VC supplementation was not significant on ΣSFA, ΣPUFA and

also ΣPUFA:ΣSFA ratio. The content and composition of FAs in the muscles, especially PUFA, are partly influenced by dietary FAs, which can easily be affected by rumen microorganisms. Due to their role as a precursor of different eicosanoids and location in cell membranes, PUFAs are essential metabolic regulators and messengers of the cell and are usually implicated in the epidemiology of cardiovascular diseases (Parodi 2016). Recent studies have indicated that a higher consumption of omega-3 FAs and a lower consumption of SFAs can lower the chances of developing cardiovascular diseases (Ramakrishnan *et al.* 2010). Supplementation of VC and the WR level in the present study did not influence the ratio of omega-6:omega-3 FAs. The ratio of Σ*n*-6:Σ*n*-3 FAs is one of the three criteria for assessing the quality of fat, with values <4.0 regarded as the recommended range or limit (Parodi 2016). The ratios (Σ*n*-6:Σ*n*-3) recorded in the present study were found to be <4. The other two criteria include total lipid content, the ratio of unsaturated FAs to SFAs, which should be >4 (Wood *et al.* 2003). The ratios of ΣPUFA:ΣSFA in this study were not significantly affected by WR and VC supplementation. However, values recorded across the experimental groups were ≥4, indicating that the meat is nutritionally good despite limited WI. The atherogenicity and desaturase indexes were not affected by the level of WR and VC supplementation. AI usually assesses the capacity of the blood vessels to form plaque. Lower AI values imply higher anti-atherogenic FA in the lipids, thereby resulting in a better chance of preventing cardiovascular disease (Woutersen *et al.* 1999). The lower AI values recorded in this study indicated that meat from water-restricted animals would not compromise consumers' health integrity. This implies that Xhosa goats at 50% WR can survive and produce meat good enough for consumption, especially to the rural poor and small farm holders' farmers of the Eastern Cape.

Conclusions

This study has demonstrated that the WR level of 70% and 50% *ad libitum* WI, with or without single and/or multiple VC supplementation, did not have a negative impact on the meat quality parameters such as oxidative stability of lipids, drip loss and ultimate pH_u. However, the slight depression in bodyweight and DMI due to suboptimum WI was lessened with VC supplementation. This implies that goat farming by the rural poor in areas affected by water limitations or shortfalls can be managed with a daily dose of VC supplementation.

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