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Relationship between Volumetric Water Footprint with Carcass and Meat Quality Characteristics Under Intensive Beef Cattle Production in South Africa

[1]Tinny Noluthando Macamba, [1]Takalani Judas Mpofu, [1]Khathutshelo Agree Nephawe, [1,2]Cuthbert Baldwin Banga, [1]Ayanda Mavis Ngxumeshe, [1]Moses Motshekwe Ratsaka, [3]Karen Munhuweyi and [1]Bohani Mtileni

[1]*Department of Animal Sciences, Tshwane University of Technology, Pretoria, South Africa*
[2]*Department of Animal Science and Production, Botswana University of Agriculture and Natural Resources, Gaborone, Botswana*
[3]*Department of Animal Production, Agricultural Research Council, Irene, South Africa*

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Corresponding Author:
Macamba Noluthando Tinny
Department of Animal Sciences,
Tshwane University of Technology,
Pretoria, South Africa
Email: noluthandomacamba12@gmail.com

Abstract: As water accessibility becomes more challenging due to the increasing human population and agricultural competition, it is crucial to select beef cattle with optimal water efficiency. The study aimed to investigate the relationship between volumetric water footprint with carcass and meat quality of beef cattle under an intensive production system. Thirty-three (33) beef cattle weaners of three different body frame sizes (small = 11, medium = 11, and large = 11), representing three different breeds of similar age and body weight groups were obtained from stud breeders. The volumetric water footprint computed were Water Intake Efficiency (WIE), Water Consumption Efficiency (WCE), and Water-Feed-Ratio (WFR). The General Linear Model was used to analyze the data and means were separated using the Fisher LSD test. Pearson moment correlation coefficient was computed to determine the relationship between the volumetric water footprint with carcass and meat quality traits ($p<0.05$). In large-frame size beef cattle, the WIE was significantly ($p<0.05$) correlated with protein percentage ($r = -0.5960$). Whereas insignificantly ($p>0.05$) correlated with meat color, proximate analyses, and carcass weights. A positive relationship ($p<0.05$) was observed between WFR and warm ($r = 0.641$) and cold ($r = 0.620$) carcass weights. In medium-frame size beef cattle, the WIE was significantly ($p<0.05$) correlated with warm carcass weight ($r = - 0.617$) and cold carcass weight ($r = 0.620$). In small-frame beef cattle, the WIE showed a significant ($p<0.05$) positive relationship with drip loss ($r = 0.710$). The WFR was only significantly ($p<0.05$) correlated with L*(lightness) meat color ($r = -0.675$). The volumetric water footprint indicators in beef cattle were not correlated to each other in the medium and large-frame size breeds, whereas in the small-frame size breed, the WCE was correlated with the WIE and WFR. Generally, there is a lack of significant associations between the volumetric water footprint indicators in all the beef cattle frame sizes with the majority of carcass and meat quality parameters.

Keywords: Beef Cattle, Water Intake Efficiency, Consumption Efficiency, Water-to-Feed Ratio, Water

Introduction

Food security is an issue both globally and at home in South Africa (SA). Grote (2018) defines food security as sufficient, safe, and healthy food. Due to the given information food security leads to health issues such as mental health problems that are caused by inaccessibility to healthy food. Therefore, people begin using strategies such as begging for food on the streets and borrowing money to buy food. Recent data indicated that there will be roughly 17.9 million houses in SA in 2021 and over 80% (14.2 million) have ample access to food, while the remaining 15% (2.6 million) and 6% (1.1 million) have insufficient and fairly limited access to food (Department of Statistics South Africa, 2022). Drought events brought on by climate change have negatively impacted water resources (Huang *et al*., 2017; Mwendera and Atyosi, 2018; Bhaga *et al*., 2020). Access to clean drinking water is becoming increasingly challenging, particularly for livestock, due to extreme weather events (Cheng *et al*., 2022). The unavoidable impact of increased pressure on water resources is attributed to the improvement of livestock farming systems.

The South African National Development Plan (NDP) 2030 and Sustainable Development Goals (SDG) argue that climate change has been shown to lower food production and the availability of drinkable water primarily due to its impact on migration dynamics and conflict levels. To that end, a call for interventions toward the worldwide effort to limit the detrimental effects of the changing climate (SDG goal 13: Climate action) Chapter 5 on climate change, and chapter 6 on modern agriculture (Africa Union Agenda 2063) was declared; to mention but a few.

The largest water user globally is the agricultural sector, utilizing the largest proportion of available freshwater, making it the most significant contributor to overall water consumption (Gleick, 2014; Ritchie and Roser, 2018). Notably, cattle are the main supplier of red meat worldwide and beef is among the most consumed red meats (Pogorzelski *et al*., 2022). With the expected exponential population growth and current climate change challenge, the food production industry will exert enormous pressure to meet food demand. The expected increase in global population raises concerns about water availability as food consumption rises, especially for animal-derived foods. It culminates in the transition from extensive livestock farming to semi-intensive and intensive production systems to suit the increasing demand (Mpandeli *et al*., 2018). The anticipated environmental impacts associated with rising consumption of animal-derived products (Sutton *et al*., 2011; Enahoro *et al*., 2019), as well as the benefits and drawbacks of intensive and extensive farming systems, have been thoroughly investigated.

Water remains an important nutrient needed by livestock, constituting more than 70% of their total body weight (Odhiambo *et al*., 1996). To sustain this tremendous amount of water, livestock obtain water through drinking, food consumption, and metabolism. Nevertheless, only a portion is assimilated into the animal's body (Meyer *et al*., 2006; Khelil-Arfa *et al*., 2012). As a result, water use efficiency is expressed as a proportion of the quantity of water absorbed and used by the cells of an animal to the overall amount of water consumed. Notably, water restriction reduces animal's dry matter and water intake, slaughter weight, and hot and cold carcass weight (Dos Santos *et al*., 2019).

To overcome the crisis of water scarcity and high demand for food (Gerbens-Leenes *et al*., 2013; Palhares *et al*., 2017), farmers need to use cattle breeds that utilize water efficiently. It is essential to understand the relationship between volumetric water footprint indicators and carcass and meat quality traits. This is crucial in the selection of beef cattle that utilize water more efficiently while producing high carcass and meat quality. Therefore, this study was conducted to investigate the relationship between volumetric water footprint with carcass and meat characteristics of beef cattle under an intensive production system with different body frame sizes.

Materials and Methods

Study Area and Animals

This research was undertaken at the Agricultural Research Council: Animal production, South Africa. Thirty-three (33) beef cattle weaners of three different body frame sizes aged ±6 months of similar body weight (body weight: 217.1 kg ± standard deviation: 53.2) groups were obtained from stud breeders. The Simmental (n = 11), Bonsmara (n = 11), and Nguni (n = 11) breeds were selected as representatives of the large, medium, and small body frame-sized beef cattle, respectively. The animals were tagged, vaccinated against respiratory diseases, and dipped for external parasite control before the trial commenced. The beef cattle weaners were allocated at random to treatments in a completely randomized approach, that is, eleven (11) animals per body frame size, with each animal as a replicate unit. The animals were randomly assigned to individual pens, 11 animals per body frame size, with each animal as a replicate unit. The animals were adapted for 28 days, followed by data collection for 84 consecutive days. There was unlimited access to food and water. Table (1) shows the diet composition of the total mixed ration.

Table 1: Post-weaning diet of feedlot steers

Feed ingredients	Composition (kg/1000 kg DM)
Hominy chop	630.0
Grass hay (Eragrostis)	200.0
Soya oilcake	80.0
Molasses	60.0
Limestone	15.0
Urea	8.0
Salt	5.0
Vit/mineral premix	1.9
Nutrient	Composition (g/kg DM)
Crude protein	120.0
ADF	84.0
NDF	159.0
Ca	11.6
P	3.6

Water Efficiency Measures

Animals were weighed using an electronic platform cattle-weighing scale at the start and every two weeks throughout the experimental period. Feed intake was quantified every week by measuring the feed supplied and refused by the animals. The Water Intake (WI) of individual animals was measured daily at 08H00 in the morning before feeding.

The following water-use efficiencies were computed:

$$Water\ Intake\ Efficiency\ (WIE) = \frac{Water\ Intake\ (l)}{Weight\ gain\ (kg)}$$

$$Water\ Consumption\ Efficiency\ (WCE) = \frac{Weight\ gain\ (kg)}{Water\ Intake\ (l)}$$

$$Water - to - Feed\ ratio\ (WFR) = \frac{Water\ Intake\ (l)}{Feed\ Intake\ (kg)}$$

Slaughtering and Carcass Traits

Slaughter weight was measured in the morning and cattle were fasted feed and water overnight to ensure complete bleeding and ease of evisceration and slaughtered at the certified abattoir. Using a captive bolt gun, cattle were stunned, then slaughtered, suspended in the hind leg, and electrically stimulated. Afterward, cattle were transferred to the production line for removal of the skin, feet, head, and quartering of the carcass. After dressing, the Hot Carcass Weight (HCW) was determined, after which they were chilled for 24 h at 4°C and again weighed for the Cold Carcass Weight (CCW) determination, following the description by Cartaxo *et al*. (2009). The ultimate pH (pH_u) was determined in the longissimus dorsi muscle between the 12^{th} and 13^{th} ribs, 24 h after slaughter.

Thaw and Cooking Loss Evaluation

The thaw loss percentage of beef loin portions was calculated by comparing the mass changes between the prior freezing and the ultimate mass after thawing. After the storage period, the loin portions were taken off from the vacuum packaging, and any unneeded water on the surface was dried off with an absorbent kitchen paper roller towel before the weight of the sample was determined. Representative samples were stored in a freezer to stop any enzymatic activity or further aging. Before cooking, the samples for cooking loss were thawed at 4-7°C for 24 h and reweighed. After cooling bags to ±4°C, the loins were pulled out, dried with absorbent paper towels, and re-weighed without additional pressure. Thaw and cooking loss was computed according to the following equations:

$$Thaw\ loss = \frac{Weight\ before\ thaw - weight\ after\ thaw}{Weight\ before\ thaw} x\ 100$$

$$Cooking\ loss = \frac{Weight\ of\ raw\ LT\ lion\ after\ thawing - weight\ of\ cooked\ LT\ loin}{Weight\ of\ raw\ loin\ after\ thawing} x\ 100$$

Display Colour

Each loin portion was sliced into eleven thick steaks (3 cm thick) from three frame sized beef breeds, as well as a meat cube. Each steak from the central section was used for the display color analysis. Each steak was laid out on a food-grade polystyrene tray, coated with oxygen-permeable polyvinyl chloride film, and exposed to a simulated display lighting (1450 lx, 3500 K color temperature) at 3°C for 14 d. On days 1, 3, and 14 of the display, the surface color parameters of each steak were assessed at three randomized areas utilizing a Hunter MiniScan EZ colorimeter calibrated using standard white and black tiles. The illuminant was determined using a D65/10° illuminant and observer settings. The international Commission on Illumination (CIE) L, an, and b values were utilized to compute the Chroma and hue angles (Hunt and David, 2012).

Drip Loss

Drip loss was obtained using the method outlined by Kim *et al*. (2015). A 35 g piece of each loin part was pruned of any noticeable fat or connective tissue, then reweighed, put into an airtight container strung with a hook through nylon netting, and hung at 3°C for 48 h. Before each final weight, the sample's surface was gently wiped with absorbent paper towels to wipe out any moisture from the surface before being reweighed to compute the drip loss (%).

Warner Bratzler Shear Force Determination

Meat samples were dry-cooked in a 200°C fan-grilled oven. Turning the meat while checking the core temperature until it reaches an end temperature of 70°C. To determine the Warner Bratzler Shear force (WBS) values, samples were weighed to determine cooking loss and chilled at 16-18°C for 30 min. Eleven samples with a diameter of the core of 12.5 mm were drilled parallel to the grain of the meat. The samples were sheared 90° to the direction of the fiber with a Warner Bratzler Shear force machine with 400 mm/min speed, installed on an Instron (model, 5409; Series) and equipped with a 500 N load cell for assessing the shear force (N).

Proximate Composition

Proximate composition was evaluated following the International Standards Organization (ISO) recommended standards (fat: ISO 1443 1973, protein: ISO 937 1978, moisture: ISO 1442 1997, and ash: ISO 936 1998).

Samples were initially freeze-dried prior to further analyses. The moisture content of meat was evaluated by desiccating samples for 24 h at 105°C to get a constant weight. The Kjeldahl procedure was used to assess the crude protein concentration, whereas the ash was evaluated after burning at 550±25°C. The Soxhlet device (Sigma-Aldrich, Buchs SG, Switzerland) with ether as a solvent, was used to analyze the crude fat. Final results were expressed on a wet basis.

Statistical Analysis

Repeated measures techniques of MiniTab 17 (2010) in proc mixed, considering the covariance structure of the observed data, were used to analyze the water use efficiency data. The statistical model used was:

$$Y_{ijk} = \mu + T_i + \varepsilon_{ij} + W_k + (TW)_{ik} + \varepsilon_{ijk}$$

where, Y_{ijk} = measurement of response (WIE, WCE, and WFR when the time was included as a classification variable) on the j^{th} herd of the ith frame size (small, medium, and large) at the k^{th} time (weeks), μ = overall mean, T_i = fixed influence of beef frame size (small, medium and large), W_k = fixed influence of the k^{th} time on measurements (k = 1, 2, 3), $(TW)_{ik}$ = interaction between i^{th} frame sizes and k^{th} time, ε_{ij} = random influence associated with the j^{th} house on the i^{th} breed group, ε_{ijk} = random error associated with the k^{th} animal in the i^{th} frame size at the j^{th} time.

For carcass and meat quality traits, the General Linear Model (GLM) of MiniTab 17 (2010) was utilized to analyze the data, whereas, the mean separation was conducted using the Fisher LSD test ($p<0.05$). Pearson moment correlation coefficient was computed to determine the relationship between volumetric water footprint indicators and carcass and meat traits ($p<0.05$):

$$Y_{ij} = \mu + T_i + \varepsilon_{ij}$$

where, Y_{ij} = measurement of response (carcass and meat quality traits), μ = overall mean, T_i = fixed influence of beef frame size (small, medium, and large), ε_{ij} = random residual error.

Results

The WIE of the three South African beef cattle frame sizes differed ($p<0.05$) over time (Fig. 1). The medium frame size beef cattle breed had greater ($p<0.05$) WIE in the second week, followed by the large frame size, with the small frame size beef cattle having the lowest WIE. The WIE of the large frame size beef cattle increased drastically towards the fourth week, followed by a sharp decline towards the third and eighth week, followed by a significant increase towards the tenth week, and subsequently declined in the last week. The medium-frame size beef cattle had a WIE that increased at a slow rate from the fourth week and started to decline after the eighth week.

The WCE of the three South African beef frame sizes differed ($p<0.05$) over time (Fig. 2). The medium frame size beef cattle experienced a sudden rise ($p<0.05$) in WCE from the second to the fourth week, while small frame size beef cattle showed a sharp decrease. All the South African cattle frame sizes under study had similar ($p>0.05$) WCE from the sixth week onwards.

The WFR of medium-sized beef cattle was higher ($p<0.05$) up to the sixth week. Moreover, there was an increase in the WFR for the large frame size beef cattle during the eighth week and then increased sharply from the fourth to the twelfth week (Fig. 3). The pattern of the WFR between the small and medium frame size beef cattle was similar throughout the experimental period, with a decline from the sixth week onwards. Notably, the size of small-frame-size beef cattle increased over time.

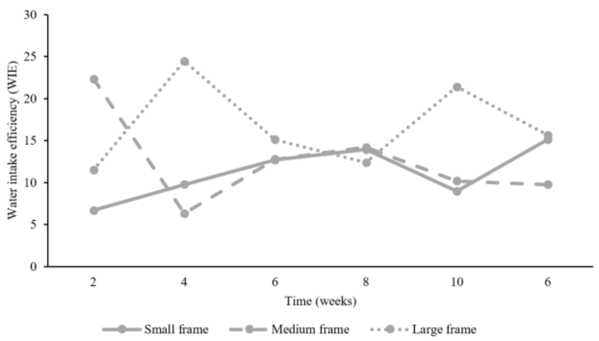

Fig. 1: Water Intake Efficiency (WIE) of three South African beef cattle frame sizes over time

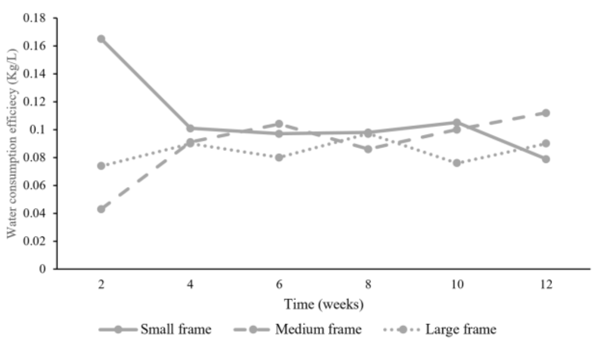

Fig. 2: Water Consumption Efficiency (WCE) of three South African beef cattle frame sizes over time

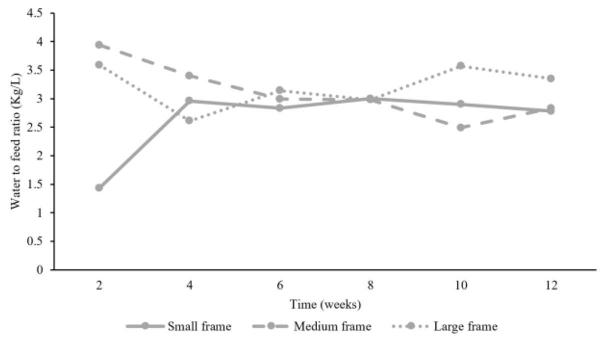

Fig. 3: Water-to-feed ratio of three South African beef cattle frame sizes over time

Table (2) shows the results of volumetric water footprint indicators, carcass composition, meat quality, and proximate analysis of three South African beef cattle frame sizes. The frame sizes of South African beef cattle influenced the WIE, WCE, and water-to-feed ratio ($p<0.05$). Furthermore, the WIE and water-to-feed ratio were more substantial in the large and medium beef cattle frame sizes ($p<0.05$) than in the small frame size. The WCE for the medium beef cattle frame size (0.09 kg/L) was comparable ($p>0.05$) to that of the large frame size (0.08 kg/L). The small-framed beef cattle yielded lower warm carcasses (166.92 kg) compared to the medium- and large-framed beef cattle. The large-frame beef cattle size carcass was of lower P8 fats compared to small and medium beef cattle frame sizes. The rib fat thickness and ultimate P^H for the three South African beef cattle frame sizes were comparable ($p>0.05$). For meat quality, beef cattle frame size significantly ($p<0.05$) influenced the L* (lightness) and a* (redness) meat color, tenderness, thawing loss, total cooking loss, freezing drying, ash, protein, fat, and moisture percentage. The medium-frame size beef cattle had a more substantial ($p<0.05$) L* (lightness) meat color (35.54) than the small (32.04) and large-frame size beef cattle (32.94). The beef cattle frame sizes studied yielded a similar ($p>0.05$) b* (yellowness) meat color. The C* (chroma) was similar ($p>0.05$) between the small (16.65), medium (16.60), and large (15.01) frame-size beef cattle. The H for the medium (50.28) was comparable ($p>0.05$) to that of the large (49.83). The H for the small-frame beef cattle (46.88) was lower compared to the medium-frame size beef cattle (50.28). The drip loss for larger frame-size beef cattle (2.17%) was lower than that of the small (3.98) and medium (3.78%) frame-size beef cattle. The medium frame breed (62.55 mm^2) yielded higher eye muscle area compared to the small (53.73 mm^2) and large (57.55 mm) frame breeds. The large frame-size beef cattle yielded highly ($p<0.05$) tender meat (3.56 kg cm^{-2}) compared to small frame-size beef cattle (2.88 kg cm^{-2}). The thawing loss for the meat of the medium-frame size beef cattle (2.78%) was comparable ($p>0.05$) to that of the large-frame size beef cattle (2.87%), whereas it was greater ($p<0.05$) compared to the small frame beef cattle (2.02%). For proximate analysis, the freeze-drying, ash, and protein percentages for the small (28.98, 1.10, and 21.16%) and medium (27.82, 1.12, and 20.91%) frame size beef cattle were greater ($p<0.05$) compared to the large frame beef cattle (24.13, 1.01 and 20.29%, respectively). The fat percentage of the meat for the small-frame size beef cattle (2.30%) was comparable ($p>0.05$) to that of the medium-frame-size beef cattle (1.65%), whereas it was greater ($p<0.05$) compared to that of the large frame beef cattle (1.27%). The meat moisture for the small frame size (74.60%) was comparable ($p>0.05$) to that of the medium frame size beef cattle (75.03%), whilst lower ($p<0.05$) than that of the large frame size beef cattle (76.70%).

Pearson's moment correlation test between the volumetric water footprint indicators and carcass quality, proximate analysis, and carcass weights of small frame size beef cattle are illustrated in Table (3). The significant negative relationship between WFR and L* (lightness) meat color ($r = -0.675$, $p<0.05$) was established. In contrast, WCE had an insignificant ($p>0.05$) positive relationship with L* (lightness) carcass color ($r = 0.464$). An insignificant ($p>0.05$) negative relationship was observed for WIE and L* (lightness) ($r =-0.141$). A significant ($p<0.05$) negative relationship was observed between the WFR and C* (chroma) ($r = -0.132$) and WFR and H (tone) ($r = -0.593$). A significant ($p<0.05$) positive relationship was established for WIE and drip loss ($r = 0.710$), while correlated with drip loss was insignificantly correlated ($p>0.05$) with WCE ($r = -0.456$) and WFR ($r = -0.091$). An insignificant ($p>0.05$) negative relationship was established for WCE and freeze-drying ($r = -0.484$). In contrast, freeze-drying had an insignificant ($p>0.05$) positive correlation with WIE ($r = 0.582$) and WFR ($r = 0.023$). The ash percentage yielded a significant ($p<0.05$) negative relationship with WIE ($r = -0.725$) and an insignificant ($p>0.05$) relationship between WCE ($r = 0.494$) and WFR ($r = -0.131$). The protein % is not correlated ($p>0.05$) with any volumetric water footprint indicator. An insignificant ($p>0.05$) relationship between the WCE and carcass eye muscle area ($r = -0.134$), rib fat thickness ($r = -0.147$), and P8 ($r =-0.331$) was also observed. An insignificant ($p>0.05$) relationship between the fat percentage and WIE ($r = 0.471$), WCE ($r = 0.324$), and WFR ($r = -0.246$) was also observed for small-frame size beef cattle. The moisture percentage was significantly ($p<0.05$) negatively correlated with WIE ($r = -0.623$) and insignificantly ($p>0.05$) correlated with WCE ($r = 0.478$) and WFR ($r = 0.120$). A significant ($p<0.05$) negative relationship between WCE and warm carcass ($r = -0.720$) and cold carcass ($r = -0.725$) was observed. P^H and WCE

Table 2: Least Square Means (LSM) and their Standard Errors (SE) for volumetric water footprint indicators, carcass composition, and meat quality of different beef cattle frame sizes

	Frame sizes		
Traits	Small	Medium	Large
Volumetric water footprint indicators			
Water intake			
Feed intake			
WIE (L/kg)	10.56^{b}±0.39	10.84^{b}±0.39	12.04^{a}±0.39
WCE (kg/L)	0.11^{a}±0.00	0.09^{b}±0.00	0.08^{b}±0.00
Water-to-feed ratio (L/kg)	2.67^{b}±0.09	2.85^{ab}±0.09	3.10^{a}±0.09
Carcass composition			
Warm Carcass (kg)	166.92^{b}±6.24	229.02^{a}±6.24	234.31^{a}±6.24
Cold Carcass (kg)	163.03^{b}±6.15	223.31^{a}±6.15	229.48^{a}±6.15
Eye Muscle Area (mm^{2})	53.73^{c}±1.69	62.55^{a}±1.69	57.55^{b}±1.69
Rib fat thickness (mm)	3.95^{a}±0.54	3.45^{a}±0.54	2.52^{a}±0.54
P8 Fat (mm)	5.55^{a}±0.56	5.62^{a}±0.56	2.61^{b}±0.56
Ultimate P^{H}	5.47^{a}±043	5.51$^{a\pm}$043	5.59$^{a\pm}$043
Meat Quality			
Color: L*(lightness)	32.04^{b}±0.64	35.54^{a}±0.70	32.94^{b}±0.79
a*(redness)	11.42^{a}±0.72	10.62^{a}±0.47	9.70^{b}±0.50
b*(yellowness)	12.09^{a}±0.63	12.73^{a}±0.39	11.42^{a}±0.43
c*(chroma)	16.65^{a}±0.93	16.60^{a}±0.55	15.01^{a}±0.62
H*(tone)	46.88^{b}±0.94	50.28^{a}±0.97	49.83^{a}±0.78
Drip loss (%)	3.98^{a}±1.65	3.78^{a}±1.27	2.17^{b}±0.87
Tenderness (kg cm^{-2})	2.88^{b}±0.14	3.19^{ab}±0.16	3.56^{a}±0.16
Thawing loss (%)	2.02^{b}±0.21	2.78^{a}±0.20	2.87^{a}±0.31
Total cooking loss (%)	20.77^{b}±0.52	23.10^{a}±0.51	19.97^{b}±1.04
Meat Proximate composition			
Freezing drying (%)	28.98^{a}±0.34	27.82^{a}±0.89	24.13^{b}±0.13
Ash (%)	1.10^{a}±0.02	1.12^{a}±0.03	1.01^{b}±0.02
Protein (%)	21.16^{a}±0.16	20.91^{ab}±0.38	20.29^{b}±0.21
Fat (%)	2.30^{a}±0.36	1.65^{ab}±0.15	1.27^{b}±0.13
Moisture (%)	74.60^{b}±0.33	75.03^{b}±0.51	76.70^{a}±0.13

$^{a\ b,c}$Row means with different superscripts differ significantly ($p<0.05$); WIE: Water Intake Efficiency; WCE: Water Consumption Efficiency, WFR: Water-to-Feed Ratio

Table 3: Pearson's moment correlation test between the volumetric water footprint indicators and meat color, proximate analysis, and carcass weights of the small frame size beef cattle

	WIE	WCE	WFR
Volumetric water footprint indicators			
WCE	-0.827**		
WFR	0.410^{NS}	-0.688**	
Meat colour			
L*(lightness)	-0.141^{NS}	0.464^{NS}	-0.675*
a*(redness)	0.539^{NS}	-0.439^{NS}	0.042^{NS}
b*(yellowness)	0.417^{NS}	-0.196^{NS}	-0.317^{NS}
c*(chroma)	0.494^{NS}	-0.332^{NS}	-0.132^{NS}
H*(tone)	-0.383^{NS}	0.563^{NS}	-0.592*
Drip loss (%)	0.710*	-0.456^{NS}	-0.091^{NS}
Meat proximate composition			
Freeze drying (%)	0.582^{NS}	-0.484^{NS}	0.023^{NS}
Ash (%)	-0.725**	0.494^{NS}	-0.131^{NS}
Protein (%)	-0.038^{NS}	0.075^{NS}	-0.309^{NS}
Fat (%)	0.471^{NS}	-0.324^{NS}	-0.246^{NS}
Moisture (%)	-0.623*	0.478^{NS}	0.120^{NS}
Carcass composition			
Warm carcass (kg)	0.489^{NS}	-0.720**	0.353^{NS}
Cold carcass (kg)	0.504^{NS}	-0.725**	0.349^{NS}

Table 3: Continue

Eye Muscle Area (mm^2)	-0.134^{NS}	-0.134^{NS}	0.544^{NS}
Rib fat thickness (mm)	0.403^{NS}	-0.147^{NS}	-0.291^{NS}
P8 (mm)	0.556^{NS}	-0.331^{NS}	-0.216^{NS}
Ultimate P^H	-0.433^{NS}	0.132^{NS}	0.298^{NS}

*p<0.05; **p<0.01; ***p<0.001; NS: Not Significant (p>0.05); WIE: Water Intake Efficiency; WCE: Water Consumption Efficiency, WFR: Water-to-Feed Ratio

Table 4: Pearson's moment correlation test between the volumetric water footprint indicators and meat color, proximate analysis, and carcass weights of medium-frame size beef cattle

	WIE	WCE	WFR
Volumetric water footprint indicators			
WCE	-0.445^{NS}		
WFR	0.130^{NS}	-0.651**	-
Meat colour			
L*(*lightness*)	0.073^{NS}	-0.313^{NS}	0.254^{NS}
a*(*redness*)	-0.004^{NS}	-0.123^{NS}	-0.175^{NS}
b*(*yellowness*)	0.082^{NS}	0.274^{NS}	0.020^{NS}
c* (*chroma*)	0.040^{NS}	-0.221^{NS}	-0.099^{NS}
H (*tone*)	0.073^{NS}	-0.090^{NS}	0.191^{NS}
Drip loss (%)	0.038^{NS}	-0.214^{NS}	-0.059^{NS}
Meat proximate composition			
Freeze drying (%)	0.314^{NS}	0.011^{NS}	-0.233^{NS}
Ash (%)	0.013^{NS}	0.433^{NS}	0.189^{NS}
Protein (%)	-0.005^{NS}	-0.024^{NS}	-0.362^{NS}
Fat (%)	0.420^{NS}	-0.213^{NS}	-0.778**
Moisture (%)	-0.177^{NS}	0.043^{NS}	0.076^{NS}
Carcass composition			
Warm carcass (kg)	-0.617*	-0.115^{NS}	-0.490^{NS}
Cold carcass (kg)	0.620*	-0.101^{NS}	-0.484^{NS}
Eye Muscle Area (mm^2)	-0.213^{NS}	-0.110^{NS}	-0.184^{NS}
Rib fat thickness (mm)	-0.247^{NS}	0.101^{NS}	0.068^{NS}
P8 (mm)	0.025^{NS}	-0.423^{NS}	-0.218^{NS}
Ultimate P^H	0.220^{NS}	0.360^{NS}	0.001^{NS}

*p<0.05; **p<0.01; ***p<0.001; NS: Not Significant (p>0.05); WIE: Water Intake Efficiency; WCE: Water Consumption Efficiency, WFR: Water-to-Feed Ratio

ultimate depicted an insignificant positive correlation (r = 0.132, p>0.05). WIE was insignificantly (p>0.05) correlated with rib fat thickness (r = 0.403), P8 (r = 0.556), carcass ultimate P^H (r =-0.433), and eye muscle area (r = -0.134), warm (r = 0.489) and cold carcass (r = 0.504; p>0.05) weights, whereas WFR was insignificantly (p>0.05) correlated with carcass ultimate PH (r = 0.298), eye muscle area (r = 0.544), rib fat thickness (r = - 0.291), P8 (r = - 0.216), warm (r = 0.353) and cold (r = 0.349) carcass weights. WIE and WCE showed significant (p<0.05) negative relationships (r =-0.827), while the relationship between WIE and WFR (r = 0.410) was positive and insignificant (p>0.05). There was a significant (p<0.05) negative relationship between the WCE and WFR (r = -0.688).

Pearson's moment correlation test between the volumetric water footprint indicators and carcass quality, proximate analysis, and carcass weights of medium-sized beef cattle are presented in Table (4). The L*(lightness) carcass color had an insignificant (p>0.05) positive relationship with WIE (r = 0.073 and WFR (r = 0.245). An insignificant (p>0.05) negative correlation was observed for L*(lightness) and WCE (r = -0.313). An insignificant (p>0.05) relationship between freeze-drying and WIE (r = -0.314), WCE (r = 0.011), and WFR (r = -0.223) was also observed in medium-frame size beef cattle. Notably, the volumetric water footprint indicators (WIE, WCE, and WFR) in the medium frame size beef cattle were insignificantly (p>0.05) correlated with each other and ultimate P^H, eye muscle area, rib fat thickness, P8, and all other proximate analysis parameters, except a significant (p<0.05) relationship was noted for the fat percentage and the WFR (r = -0.778). A significant (p<0.05) negative relationship between warm carcass weight and WIE (r = -0.617, was also observed. Cold carcass weight and water intake efficiency were positively (p<0.05) correlated (r = 0.620). The relationship between WCE and WFR (r = -0.651) was noted to be significant (p<0.05).

Table 5: Pearson's moment correlation test between the volumetric water footprint indicators and meat color, proximate analysis, and carcass weights of large frame size beef cattle

	WIE	WCE	WFR
Volumetric water footprint indicators			
WCE	0.035^{NS}	-	
WFR	-0.165^{NS}	-0.275^{NS}	-
Meat color			
L*(*lightness*)	0.030^{NS}	0.402^{NS}	0.398^{NS}
a*(*redness*)	0.038^{NS}	-0.319^{NS}	0.026^{NS}
b*(*yellowness*)	0.151^{NS}	0.080^{NS}	0.395^{NS}
c* (*chroma*)	0.096^{NS}	-0.127^{NS}	0.346^{NS}
H (*tone*)	0.104^{NS}	0.657*	-0.028^{NS}
Drip loss (%)	-0.172^{NS}	0.219^{NS}	0.468^{NS}
Meat proximate composition			
Freeze drying (%)	0.091^{NS}	0.042^{NS}	0.294^{NS}
Ash (%)	0.309^{NS}	0.088^{NS}	-0.274^{NS}
Protein (%)	-0.596*	0.224^{NS}	-0.122^{NS}
Fat (%)	0.266^{NS}	0.126^{NS}	-0.005^{NS}
Moisture (%)	-0.055^{NS}	-0.130^{NS}	-0.193^{NS}
Carcass composition			
Warm carcass (kg)	-0.406^{NS}	-0.163^{NS}	0.641*
Cold carcass (kg)	-0.409^{NS}	0.165^{NS}	0.620*
Eye Muscle Area (mm^2)	0.235^{NS}	0.049^{NS}	0.667^{NS}
Rib fat thickness (mm)	-0.412^{NS}	0.082^{NS}	0.211^{NS}
P8 (mm)	-0.188^{NS}	0.346^{NS}	0.046^{NS}
Ultimate P^H	0.366^{NS}	-0.252^{NS}	-0.194^{NS}

*p<0.05; **p<0.01; ***p<0.001; NS: Not Significant (p>0.05); WIE: Water Intake Efficiency; WCE: Water Consumption Efficiency, WFR: Water-to-Feed Ratio

Pearson's moment correlation test between the volumetric water footprint indicators and carcass quality, proximate analysis, and carcass weights of large frame-size beef cattle are presented in Table (5). However, the volumetric water footprint indicators were insignificantly (p>0.05) correlated with the eye muscle area, rib fat thickness, P8, L*(lightness), b*(yellowness), a*(redness), and c*(chroma) in the large frame size beef cattle. In addition, WCE and h*(tone) were observed to be positive significantly (p<0.05) correlated (r = 0.657). For proximate analyses. The freeze-drying percentage, ash percentage, fat, and moisture percentage depicted an insignificant (p>0.05) relationship with all the volumetric water footprint indicators. A significant (p<0.05) negative relationship between the protein percentage and WIE (r = -0.596) was established. Fat percentage was insignificantly (p<0.05) correlated with WIE (r = 0.266), WCE (r = 0.126), and WFR (r = -0.005). WFR was observed to be significantly (p<0.05) positively correlated with warm (r = 0.641) and cold (r = 0.620) carcass weights. Notably, volumetric water footprint indicators (WIE, WCE, and WFR) in the large-frame-size beef cattle were insignificantly (p<0.05) correlated with each other and the ultimate P^H.

Discussion

The present study evaluated the relationship between volumetric water footprint indicators and carcass and meat quality traits in South African beef cattle of different frame sizes. No single frame size is optimal for all feed resources, mating systems, and market requirements (Mwendera *et al*., 2014; Hozáková *et al*., 2020). Matching cow size to the environment involves an evaluation of the state of the environment (Şentürklü *et al*., 2021). Overall, the economic return ought to define the ideal frame size for the specific condition (Kluyts *et al*., 2004; Şentürklü *et al*., 2021).

It was observed that medium and smaller breeds utilize water more efficiently for post-weaning growth performance, as shown by their superior WIE, WCE, and WFR. This indicates that the small frame-sized breed had a better gain per L of water consumed compared to the large frame-sized animals. This concurs with the argument put forward by several researchers (Brew *et al*., 2011; Ahlberg *et al*., 2018) that animals with low water intake utilize water more efficiently relative to their dry matter feed intake and body size. Leeuw and Sanele (2020) are of the view that small frame-size cattle, such as Nguni, will be the breed of choice in the future owing to their low water requirements. Animals with higher water-use efficiency are desirable (Brew *et al*., 2011; Ahlberg *et al*., 2018). Furthermore, in drier areas where the water quality is poor, it would be advantageous to rear cattle breeds that possess minimal water consumption and excellent utilization of existing water resources.

The greater hot carcass weight of large frame size breeds compared to small frame size breeds was consistent with earlier research (Camfield *et al*., 1999; Şentürklü *et al*., 2021) and could be attributed to the larger size and weight of the large frame size breed at slaughter compared to the small frame size. It was further noted that the large and medium frame size breeds yielded similar warm and cold carcass weight, this could be because the medium frame size is a composite beef breed specifically developed for improved growth and weight (Bonsma, 1980; Bergh *et al*., 2010). Unlike our observations, (Collier *et al*., 2015) reported similar hot carcass weights between beef cattle of different frame sizes; however, this was not translated into cold carcass weight, as these beef cattle frame sizes yielded different cold carcass weights.

In the present study, the large-framed cattle breed yielded higher warm and cold carcass weights than the small-framed breeds. Comparable findings have been reported in the literature (Duckett *et al*., 2014; Şentürklü *et al*., 2021; Strickland *et al*., 2024). This could be because the Simmental breed is known for its faster growth rate (Deland and Newman, 1991; Oprzadek *et al*., 2001), which could be translated into both warm and cold carcass weights. Ćirić *et al*. (2017) reported that the hot and cold carcass weight of Simmental beef cattle has a positive relationship with the slaughter weight.

Beef cattle of European origin, such as simmental and angus, are known to grow faster and have higher carcass weights than those of African descent, such as Nguni and Bonsmara (Mwai *et al*., 2015). In extensive grazing systems, beef cattle of different frame sizes also yielded different carcass weights, wherein a large frame size yielded a significantly higher carcass weight compared to smaller frame sizes (Du Plessis and Hoffman, 2007).

Meat quality traits, such as L*(Lightness), a*(redness), drip loss, tenderness, thawing, and cooking loss, differed between the beef cattle frame sizes. Beef quality variability has been attributed to genetic differences in lines or breeds (Liu *et al*., 2020; Conanec *et al*., 2021; Strydom *et al*., 2001), variations resulting from the crossing of breeds, and variations among animals (Garcia *et al*., 2013).

Contrary to our findings, Du Plessis and Hoffman (2007) observed similar cooking loss and drip loss in beef cattle of different frame sizes in extensive grazing. The observed difference with these researchers could be because the animals of the present study were reared in an intensive system. Alternatively, Rodríguez-Vázquez *et al*. (2020) observed that Rubia Gallega calves reared in different production systems yielded different cooking and drip losses. In contrast to the observations of (Rodríguez-Vázquez *et al*., 2020; Fonteh *et al*., 2016), calves reared in different systems yielded similar drip loss. Furthermore, the finding that the drip loss of the large frame size was lower than that of small and medium frame sizes could be attributed to a greater level of protein denaturation (Akhtar *et al*., 2013; Hughes *et al*., 2014).

Beef quality of small frame size (Nguni) (Mapiye *et al*., 2010; Strydom *et al.*, 2001), medium frame size (Bonsmara) (Muchenje *et al*., 2008; Webb *et al*., 2018), and large frame size (Simmental) (Wang *et al*., 2021) have been reported. Several factors influence meat tenderness, including the structure of a particular muscle (Dominguez-Hernandez *et al*., 2018), the post-mortem process (Hulánková *et al*., 2018), the breed (Xie *et al*., 2012) and age of the animal (Kopuzlu *et al*., 2018; Soulat *et al*., 2023). Their variation was observed in meat tenderness, cooking, and drip loss among beef cattle of different frame sizes. Contrary to our observations, similar meat tendernesses (Cafferky *et al*., 2019; Şentürklü *et al*., 2021) and cooking losses (Duckett *et al*., 2014; Şentürklü *et al*., 2021) were observed in beef cattle with different frame sizes. The observed differences in meat tenderness between beef cattle of different frame sizes could be attributed to the fact that this trait is influenced by the selection and genotype of the cattle (Hanzelková *et al*., 2011; Xie *et al*., 2012). Similar to our observations, cooking (Cafferky *et al*., 2019; Şentürklü *et al*., 2021) and drip loss (Cafferky *et al*., 2019) did not differ among beef cattle of different frame sizes.

Meat colors b*(yellowness), a*(redness), and L*(Lightness) were similar between beef cattle frame sizes (Du Plessis and Hoffman, 2007). A similar trend was observed only for b* (yellowness) in the present study. The present finding that b*(yellowness) meat color does not vary between frame sizes has also been observed in previous studies (Du Plessis and Hoffman, 2007; Cafferky *et al*., 2019). Furthermore, in the present study, it was observed that a*(redness) and L*(Lightness) meat colors differed between different frame sizes. Contrary to our findings, several studies (Xie *et al*., 2012; Duckett *et al*., 2014; Cafferky *et al*., 2019) reported comparable a*(redness) and L*(Lightness) meat color parameters between different frame sizes. More importantly, the breed of beef cattle is a significant source of variation in meat color parameters (Chulayo and Muchenje, 2016).

The variation in eye-muscle area, P8 and rib fat thickness observed among the different frame sizes of beef cattle in the current study is comparable with those in the literature (Piao and Baik, 2015; Park *et al*., 2018). The eye muscle area of the medium frame was higher than that of the small frame size in beef cattle. This is in line with the expectation that larger breeds will have more muscle mass than smaller breeds. This was expected, given an account of the literature (Duckett *et al*., 2014; Şentürklü *et al*., 2021), that the eye muscle area was greater in large than in small-frame beef cattle breeds. However, this may indicate that large-frame breeds have a faster rate of muscling than small-frame breeds (Nqeno, 2008). On the contrary, (Muchenje *et al*., 2008) reported that small frame-sized beef cattle such as nguni and medium frame such as Bonsmara reared on natural pastures have similar eye muscle areas. The observed difference with our findings could be attributed to the difference in the production system, that is, intensive vs. extensive grazing systems, of these two studies.

It is essential to take into account that the higher water-use efficient cattle in the present study, that is, medium frame, had higher rib fat thickness, eye muscle area, and P8 fat. Days on feed could be shortened for these cattle and feed costs would decrease if the market required low-fat distribution in the carcass. Such shortening of the feedlot period can reduce water consumption, feed consumption, and thus profitability of farming enterprises. Smaller mature-sized beef cattle have a greater fat depth than larger mature beef cattle (Schreurs *et al*., 2008). The small and medium-frame breeds were observed to have more rump fat than the large frame, as depicted by the higher P8 fat.

The finding that the frame size of beef cattle affects the chemical composition is in line with several reports (Strydom *et al*., 2001; Muchenje *et al*., 2008; Xie *et al*., 2012; Wang *et al*., 2021). Nevertheless, the parameters observed in several studies (Strydome *et al*., 2001; Muchenje *et al*., 2008; Xie *et al*., 2012) were higher than those observed in this study, therefore, the variation could be ascribed to the hormonal effects and fact that the animals were slaughtered at different ages in these studies.

To our knowledge, this has become the very first research to determine the relationship between volumetric water footprint indicators and carcass and meat quality traits. Interesting correlations were found among the traits examined in the present study. Notably, the WIE, WCE, and WFR were affected by beef cattle frame size. These traits were not correlated with each other in the large and medium frame size breeds, whereas in the small frame size breed, WCE was correlated with WIE and WFR. In the present study, WIE in small frame size breeds was negatively correlated with WCE, drip loss, ash, and moisture content. This trend indicates that particular animals in the small frame have a greater overall quality than others within the study. For example, small-frame animals exhibiting greater WIE values exhibited lower WCE, drip, ash, and moisture %, indicating that these traits are associated with superior water use efficiency in small-frame breeds. The multifaceted relationship among these traits contends that improving one of the traits might benefit the other traits.

Moreover, WIE correlated with cold and warm carcass weights, whereas WFR correlated with fat %. The observed correlation could be translated to the fact that if the medium-sized beef cattle manage to have greater WIE, the cold carcass weight is also expected to be high. This means that WIE could be used as an indicator trait for cold and warm carcass weight. The negative correlation between the WFR and fat % means that if the small frame size beef cattle have a greater WFR, the animal is expected to have less fat % in the meat.

In large frame-size cattle, WFR was positively correlated with warm and cold carcass weight. An increase in the WFR would consequently lead to increased cold and warm carcass weights in large-frame beef cattle. The positive correlation between the WIE and protein % means that a greater WIE will consequently lead to a reduction of protein in the meat of the large frame size. Therefore, selection for greater WIE will lead to a reduced protein % in the meat of the large-frame size beef cattle. Generally, there is a lack of significant associations between volumetric water footprint indicators in all beef cattle frame sizes with the majority of meat color, proximate analysis, and carcass traits.

Findings from this research contribute to Goal 13 (Climate Action) of the United Nations Sustainable Development Goals and align well with the Africa Union Agenda 2063 and the South African National Development Plan (NDP) Vision 2030 chapter 5 on climate change and chapter 6 on modern agriculture.

Conclusion

These results reveal that the medium-sized breed outperformed the small and large frame-size breeds in terms of water consumption efficiency under an intensive production system. Notably, the volumetric water footprint indicators (WIE, WCE, and WFR) were affected by beef cattle frame size. These traits were not correlated to each other in the medium and large frame size breed, whereas in the small frame size breed, the WCE was correlated with the WIE and WFR. Generally, there is a lack of significant associations between volumetric water footprint indicator traits in all beef cattle frame sizes with the majority of carcass and meat quality parameters under these experimental conditions.

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Author’s Contributions

Tinny Noluthando Macamba: Collected the data and conducted all trials, analyzed data, and drafted the article.

Takalani Judas Mpofu, Khathutshelo Agree Nephawe, Cuthbert Baldwin Banga, Ayanda Mavis Ngxumeshe, Moses Motshekwe Ratsaka, Karen Munhuweyi and Bohani Mtileni: Designed the experiment, coordinated the experiment, provided statistical analysis and corrected the manuscript.

Ethics

Tshwane University of Technology (TUT) Animal Research Ethics Committee (AREC202211001) and Agricultural Research Council (17/1/1/2/1/72) approved the study.

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