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Carcass Characteristics and Meat Quality of Ross 308 Broiler Chickens Fed Malted Red and White Sorghum-Based Diets

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Abstract: In this study, the effects of malted sorghum-based diets (MSBD) on carcass characteristics and meat quality were investigated in broiler chickens. Two-week-old Ross 308 broilers were randomly allocated to three groups (each with five replications) and were then reared on either 0 or 100% (red (Mr Buster) or white (Segaolane)) malted sorghum commercial diets. The highest ($p < 0.05$) slaughter weights, hot carcass weights, and cold carcass weights were observed for the broilers reared on the control diets. Broilers reared on MSBD had high ($p < 0.05$) drumstick–thigh and vertebrae weights. The broilers fed the malted red sorghum-based diet (MRSBD) had the longest ($p < 0.05$) small intestine and highest gizzard and liver percentage. The pHi of the broilers fed MRSBD was higher ($p < 0.05$) than the broilers on the control or malted white sorghum-based diet (MWSBD). Breast muscle crude fibre was the lowest ($p < 0.05$) for the MRSBD and phosphorus was low ($p < 0.005$) for MSBD broilers. The highest ($p < 0.05$) muscle potassium and magnesium was found in the control diet broilers. The carcass characteristics, internal organs, and meat quality traits of the broilers fed MSBD compared well to those fed the control diets. It is concluded that malted sorghum grains are a potential alternative energy source to maize for broiler diets and could reduce competition for maize grains between livestock and human use.

Keywords: broilers; carcass characteristics; Mr Buster; malted sorghum; Segaolane

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1. Introduction

It is common practice to use maize as a major source of dietary energy in poultry and human nutrition, as well as for industrial use [1]. The multiple uses of maize create stiff competition among humans, livestock, and industry, leading to its price in the market becoming unpredictably high, and therefore becoming unsustainable for small and medium-scale poultry farmers. However, to save the collapse of the poultry sector, there is a need to search for and evaluate alternative energy sources such as sorghum.

In comparison to maize, sorghum can be grown successfully on relatively poor soils with lower moisture characteristics, such as in semi-arid environments [2,3]. This is due, among other things, to superior leaf physical and physiological attributes when exposed to stressful conditions [4]. The metabolizable energy (ME) and crude protein (CP) content of sorghum are 13.4 MJ/Kg and 9.5%, respectively, compared with 14.2 MJ/Kg ME and 10.1% CP, respectively, for maize [5]. However, the major constraint on the efficient utilisation of sorghum in poultry diets is the presence of high amounts of anti-nutritional factors (ANFs) such as tannins that depress poultry performance [6]. Tannins present in chicken diets reduces feed intake due to reduced palatability, resulting in low live weight gain, low digestibility, and poor feed conversion efficiency [7]. However, white sorghum varieties contain lower polyphenol concentrations, which should be advantageous as concentrations of total phenolic compounds are negatively correlated with ME:GE ratios [8], opening an opportunity to utilize white sorghum in poultry feeding.

Sorghum varieties are continuously being improved by plant breeders and reduced tannins greatly improving nutrient digestibility for poultry [3]. Recently varieties released in Botswana [9] and analysed for tannins by Badubi [10] may fit this purpose. In addition, physical, chemical and biological treatments can be used to upgrade cereals for different uses, including use as animal feed. Medugu et al. [11] have reported that the fermentation process improves feed utilisation in poultry. A study by Fafiolu et al. [12] concluded that up to 300 g/kg of malted sorghum sprout can be fed to growing pullets without any adverse effect. It is for these reasons that treated sorghum which, at present, has limited alternative uses, is being proposed by the present study for application in the feeding of broiler chickens. Therefore, it is imperative that, when fed to poultry, malted sorghum diets are assessed, not only for feed intake or conversion efficiency but also for carcass and meat quality. This is because the ultimate test for food animal products is their acceptability by consumers. Therefore, the present study was undertaken to evaluate the effects of malted sorghum-based diets (malted red or white grains) on the carcass characteristics and meat quality of broiler chickens.

2. Materials and Methods

2.1. Study Site and Ethical Consideration

The study was carried out at the Botswana University of Agriculture and Natural Resources (BUAN), Content Farm, Sebele, Gaborone, Botswana. The university is located 24°36′40.90′′ S and 25° 56′13.35′′ E at 994 m above sea level.

2.2. Feed Formulation

Unscreened white (Segaolane; MWSBD) and red (Mr Buster; MRSBD) sorghum grains were purchased from Botswana Agricultural Marketing Board (BAMB) in Gaborone, Botswana, and malted following the procedure explained by Legodimo and Madibela [13]. Three iso-energetic and iso-nitrogenous experimental diets (Table 1) in a mash form were formulated as described by Mabelebele et al. [14] to meet the nutritional requirements for the grower and finisher broiler chickens by totally replacing yellow maize with malted sorghum (Table 2). The diets were as follows; 1. Control diets (commercial grower and finisher broiler diets containing yellow maize grain); 2. MRSBD (100% malted red sorghum replacing maize in a commercial diet); 3. MWSBD (100% malted white sorghum replacing maize in a commercial diet). The nutrient composition of the dietary treatments was then analysed according to the methods by the Association of Official Analytical Chemists [15].

Table 1. Ingredients (g/kg) of experimental diets provided to Ross 308 from 2 to 6 weeks of age on an air-dry basis.

	Experimental Diets		
Ingredients	**Control**	**MSBD**	**MBBD**
	Grower		
Soya oil cake	104.7	104.70	104.70
Full fat soya	180.00	180.00	180.00
Malted sorghum grains	0.00	642.70	642.70
Maize grains	642.70	0.00	0.00
* Amino acids and mineral premix	39.30	39.30	39.30
Total	1000.00	1000.00	1000.00
	Finisher		
Soya oil cake	145.60	145.60	145.60
Full fat soya	90.40	90.40	90.40
Malted sorghum grains	0.00	730.02	730.20
Maize grains	730.20	0.00	0.00
Amino acids and mineral premix	33.80	33.80	33.80
Total	1000.00	1000.00	1000.00

* = Company confidential information.

Table 2. Nutrient composition (%, unless stated otherwise) of experimental diets provided to Ross 308 from 2 to 6 weeks of age on an air-dry basis.

	[1] Experimental Diets		
Nutrient	**Control**	**MWSBD**	**MRSBD**
	Grower		
Dry matter	93.81	93.61	93.41
Ash	7.94	7.17	9.92
Organic matter	92.06	92.83	91.08
Crude protein	22.79	22.40	23.02
Energy (MJ/Kg)	18.11	18.33	18.32
Crude fat	7.52	8.78	7.79
Crude fibre	13.31	13.23	14.36
Condensed Tannin	0.045	0.056	0.057
	Finisher		
Dry matter	93.47	92.81	93.20
Ash	6.96	9.68	8.46
Organic matter	93.04	90.32	91.54
Crude protein	21.49	21.62	22.11
Energy (MJ/Kg)	18.50	18.45	18.58
Crude fat	7.85	8.06	7.35
Crude fibre	13.62	13.74	14.87
Condensed Tannin	0.049	0.053	0.071

[1] Experimental diets: control = a standard commercial starter, grower and finisher diet without malted sorghum; MWSBD = malted white sorghum-based diet; MRSBD = malted red sorghum-based diet.

2.3. Experimental Design and Management of Birds

A total of 150 broilers were purchased from a local supplier (Ross Breeders hatchery, Gaborone, Botswana). Before the arrival of the experimental chicks, the poultry house was cleaned. All dust was removed exposing all surfaces to a detergent. The equipment was washed with virkon (virucidal disinfectant). Upon arrival, the broilers were fed commercial starter from Opti feeds (Gaborone, Botswana) for the first 2 weeks. Thereafter, they were individually weighed, balanced and blocked by weight and allocated to 15 pens (each pen measuring 2.3 × 1.24 m). The 15 pens were then assigned to the 3 experimental diets in a completely randomised design and each dietary treatment had 5 replications (pens) with 10 chicks per pen. The broilers were raised on a deep litter system bedded with wood shaving from Agricfeeds Botswana, Gaborone, Botswana, under natural lightning until slaughter after 6 weeks of feeding.

2.4. Slaughter Procedure, Carcass Traits and Visceral Organ Measurements

At the end of the 6 weeks, all the chickens were weighed to obtain the slaughter weight (SW) and 15 chickens (3 chickens/pen) were randomly sampled from each treatment for carcass characteristics. Broilers were fasted for 12 h to prevent the contamination of the carcasses with digesta and faeces. The broilers were electrically stunned and slaughtered by cutting the jugular vein and allowed to bleed for 3 min. They were scalded at 65 °C in water for 55 s, then defeathered in a rotary drum picker for 20 s and manually eviscerated. After evisceration, the carcasses were weighed to obtain the hot carcass weight (HCW). Hot carcass yield (HCY) was calculated as the proportion of HCW to SW. The SW and the HCW were used to determine the dressing out percentage (Equation (1)). Carcasses were then chilled at 4 °C for 24 h and then re-weighed to obtain the cold carcass weights (CCW). The weights of the hot carcass cuts (breast, wings, thighs–drumsticks, and vertebrae back) and visceral organs (liver, gizzard and heart) were taken from the three (3) randomly selected broilers per replicate (pen) using the OXO electronic scale (Explorer EX 224, OHAUS Corp., Beijing, China). The values were expressed as a proportion of HCW and referred to as an index. The small intestine and large intestine (colon + caecum) were measured using Tailor's flexible measuring tape (Feed Centre Botswana, Gaborone, Botswana). Equations (2) and (3) were used to compute breast muscle and thigh–drumstick percentage relative to the carcass.

$$\text{Dressing out percentage} = \frac{\text{HCW (g)}}{\text{SW (g)}} \times 100 \quad (1)$$

$$\text{Breast muscle percentage} = \frac{\text{Breast muscle(g)}}{\text{HCW(g)}} \times 100 \quad (2)$$

$$\text{Drumstick percentage} = \frac{\text{Drumstick (g)}}{\text{HCW(g)}} \times 100 \quad (3)$$

2.5. Meat pH

A portable digital pH meter (CRISON pH25, CRISON Instruments SA, Alella, Spain) with a piercing electrode was used to measure the breast pH at 45 min (initial pH; pH_i) and 24 h post-slaughter (ultimate pH; pH_U) [16]. The pH meter was calibrated using buffer solution at pH 7.

2.6. Proximate Analysis of Breast Muscle

The proximate analysis of the subsample of the breast muscle was subjected to chemical analysis according to the methods by the Association of Official Analytical Chemists [15]. Dry matter (method number 930.15), organic matter (method number 924.05), protein (method number 984.13), and crude fibre (CF, ANKOM Technology, Macedon, NY, USA) were determined. Crude fat was analysed using Soxlet methods (method number 960.39).

2.7. Mineral Content of Breast Muscle

The frozen breast meat (stored at −4 °C) was allowed to thaw at room temperature and a 10 g sub-sample was obtained by coring to obtain muscle disks. This was then analysed for ash and mineral composition [15]. Ash content was determined by ashing the breast meat at 550 °C for 6 h in a blast furnace (method number 924.05). Calcium (Ca), magnesium (Mg), potassium (K), and sodium (Na) from the breast meat were analysed using an inductively coupled plasma mass spectrometer from Perkin Elmer supplier (Greenville, SC, USA). Phosphorus (P) was determined calorimetrically using sodium phenol and ammonium molybdate plus the ascorbic acid method (method number. 976.06).

2.8. Data Analysis

Data on the carcass characteristics, internal organ size, and meat quality parameters were analysed using one-way analysis of variance (ANOVA) using the general linear model (GLM) procedures of SAS [16] according to the following model:

$$\gamma_{ijk} = \mu + d_i + \varepsilon_{ijk}$$

where γ_{ijk} = response variable; μ = general mean; d_i = diet (fixed effects); ε_{ijk} = random error associated with observation; and ijk = is assumed to be normally and independently distributed. Treatment means were separated using the least square means. The level of significance was set at $p < 0.05$.

3. Results

Table 3 shows that there were significant dietary effects on the carcass traits of the broilers with the exception of pH_U. The broilers fed the control diet had the highest ($p < 0.05$) slaughter, HCW, and CCW, followed by those fed MWSBD, and lastly those fed MRSBD. Higher ($p < 0.05$) HCY and dressing percentage were observed in broilers fed the control diet compared to those fed the malted sorghum-based diets (MSBD), which did not differ ($p > 0.05$) from each other. Broilers fed MSBD had heavier ($p < 0.05$) wings compared to those fed the control diet. However, those fed the control diet and MRSBD had similar ($p > 0.05$) breast weights, while MRSBD also had similar ($p > 0.05$) breast weights to those fed MWSBD. The broilers fed MSBD had a heavier thigh–drumstick weight (TDW) %, higher thigh–drumstick weight ratio (TDWR), and higher vertebrae weight compared to those fed the control diets. Significantly higher pH_i ($p < 0.05$) of muscle was observed in the broilers fed the control diets and MWSBD compared to those fed MRSBD.

Table 3. Effects of substituting maize in broiler diets with malted red or white sorghum on carcass traits and the weight of the external organs in 6-week-old Ross 308 broiler chickens (mean ± SEM).

	[1] Experimental Diets			
Parameters	**Control**	**MWSBD**	**MRSBD**	***p*-Value**
Slaughter weight (g)	2212.4 ± 33.1 [a]	2101.4 ± 33.5 [b]	1933.8 ± 33.5 [c]	0.0001
Hot carcass weight (g)	1719.5 ± 26.5 [a]	1594.5 ± 26.8 [b]	1450.5 ± 26.8 [c]	0.0001
Cold carcass weight (g)	1694.1 ± 26.5 [a]	1570.8 ± 26.8 [b]	1421.6 ± 26.8 [c]	0.0001
Hot carcass yield (%)	76.2 ± 0.7 [a]	74.1 ± 0.7 [b]	73.3 ± 0.7 [bc]	0.02
Dressing percentage (%)	75.4 ± 0.7 [a]	73.4 ± 0.7 [b]	72.26 ± 0.7 [bc]	0.008
Wing weight (%)	5.5 ± 0.09 [c]	5.7 ± 0.09 [ab]	5.8 ± 0.09 [a]	0.10
Breast weight (%)	33.5 ± 0.7 [a]	31.1 ± 0.7 [b]	31.8 ± 0.7 [ab]	0.03
Breast weight ratio	33.5 ± 1.0 [a]	31.1 ± 1.0 [b]	31.8 ± 1.0 [ab]	0.03
Thigh–drumstick weight (%)	13.7 ± 0.2 [b]	14.7 ± 0.2 [a]	14.7 ± 0.2 [a]	0.06
Thigh–drumstick weight ratio	13.7 ± 0.34 [b]	14.7 ± 0.3 [a]	14.7 ± 0.3 [a]	0.06
Vertebrae (back) weight (%)	9.6 ± 0.3 [b]	10.8 ± 0.3 [a]	10.6 ± 0.3 [ab]	0.08
pH_i	5.8 ± 0.1 [a]	5.9 ± 0.1 [a]	5.6 ± 0.05 [b]	0.0002
pH_u	5.5 ± 0.04	5.5 ± 0.04	5.6 ± 0.04	0.40

[a,b,c] Means in the same row with different superscripts are significantly different ($p < 0.05$); [1] Experimental diets: control = a standard commercial starter, grower and finisher diet without malted sorghum; MWSBD = malted white sorghum-based diet; MRSBD = malted red sorghum-based diet.

Apart from small intestine and caeca, all internal organs were affected by experimental diets (Table 4). Chickens fed the control diet had a shorter ($p < 0.05$) large intestine and lighter liver weight compared to those fed malted sorghum-based diets, which did not differ ($p > 0.05$) between themselves. The broilers fed MRSBD had heavier ($p < 0.05$) gizzards followed by those fed MWSBD, and lastly those fed the control diet. A heavier heart ($p < 0.05$) was observed from the broilers fed MRSBD compared to those fed the control diet and MWSBD, with the latter two being similar ($p > 0.05$).

Diet did not affect the chemical composition of the breast muscle of the broilers, except for crude fat content (Table 5). Breast muscle from broilers fed MRSBD had the lowest ($p < 0.05$) crude fat content compared to those fed the control diet. However, there were no significant ($p > 0.05$) differences observed in the crude fat content of the breast muscle of broilers fed MWSBD and the control diet.

Table 6 shows that there were significant dietary effects on the mineral concentration of breast muscle. The breast muscle of chickens fed MRSBD had a lower ($p < 0.05$) P content compared to those fed the control diet, but no difference in P concentration was observed between broilers fed the malted sorghum-based diets. The calcium levels in breast muscle of broilers fed MWSBD were the lowest compared to those fed the control diet and MRSBD. The broilers fed MRSBD had the highest ($p < 0.05$) content of Na in their breast muscle, followed by those fed MWSBD and lastly those fed the control diet. The potassium and Mg content of the breast muscle of the broilers fed malted sorghum-based diets was significantly higher compared to those fed the control diet.

Table 4. Effects of substituting maize in broiler diets with malted red or white sorghum on the size of the internal organs (% of HCW, unless stated otherwise) in 6-week-old Ross 308 chickens.

	[1] Experimental Diets				
Parameters	**Control**	**MWSBD**	**MRSBD**	**[2] SEM**	***p*-Value**
Large intestine length (mm)	80.5 [b]	82.9 [ab]	91.5 [a]	2.64	0.02
Small intestine length (mm)	1585.0	1181.6	1670.8	46.9	0.60
Caeca (mm)	263.0	176.4	165.2	38.0	0.41
Liver	2.1 [b]	2.2 [a]	2.2 [a]	0.03	0.05
Gizzard	1.5 [c]	1.7 [b]	1.9 [a]	0.03	0.0001
Heart	0.5 [b]	0.6 [b]	0.6 [a]	0.02	0.01

[a,b,c] Means in the same row with different superscripts are significantly different ($p < 0.05$). [1] Experimental diets: control = a standard commercial starter, grower and finisher diet without malted sorghum; MWSBD = malted white sorghum-based diet; MRSBD = malted red sorghum-based diet.[2] SEM = standard error of the mean.

Table 5. Effects of substituting maize in broiler diets with malted red or white sorghum on breast chemical composition (%, unless stated otherwise) in 6-week-old Ross 308 chickens.

	[1] Experimental Diets				
Parameters	**Control**	**MWSBD**	**MRSBD**	**[2] SEM**	***p*-Value**
Dry matter	97.8	98.3	97.4	0.5	0.28
Ash	7.2	6.9	7.3	0.9	0.66
Organic matter	92.8	93.1	92.3	0.9	0.66
Energy (MJ/Kg)	22.4	22.4	22.3	0.1	0.78
Crude fat	3.6 [a]	2.8 [ab]	1.8 [b]	0.3	0.0001
Crude fibre	6.9	7.1	7.3	0.7	0.92
Crude protein	21.6	23.2	23.4	0.9	0.38

[a,b] Means in the same row with different superscripts are significantly different ($p < 0.05$). [1] Experimental diets: control = a standard commercial starter, grower and finisher diet without malted sorghum; MWSBD = malted white sorghum-based diet; MRSBD = malted red sorghum-based diet. [2] SEM = standard error of the mean.

Table 6. Effects of substituting maize in broiler diets with malted red or white sorghum on the breast macro mineral content (mg/L) of 6-week-old Ross 308 chickens.

	[1] Experimental Diets				
Parameters	**Control**	**MWSBD**	**MRSBD**	**[2] SEM**	***p*-Value**
Phosphorus	37.6 [a]	36.1 [ab]	34.2 [b]	0.84	0.04
Calcium	834.9 [a]	723.2 [b]	832.8 [a]	31.6	0.04
Sodium	923.4 [c]	1333.0 [b]	1591.7 [a]	69.5	0.0001
Potassium	4357.1 [b]	6372.7 [a]	6588.1 [a]	138.7	0.0001
Magnesium	273.1 [c]	421.3 [a]	374.9 [ab]	26.7	0.004

[a,b,c] Means in the same row with different superscripts are significantly different, $p < 0.05$. [1] Experimental diets: control = a standard commercial starter, grower and finisher diet without malted sorghum; MWSBD = malted white sorghum-based diet; MRSBD = malted red sorghum-based diet. [2] SEM = standard error of the mean.

4. Discussion

Research exploring the effects of malted sorghum on the carcass traits and meat quality of broilers are limited, making it difficult to compare the present results with any studies carried elsewhere. However, Adeboye et al. [17] and Oke et al. [18] noted a reduction in the final weight and weight gain of broiler birds and turkey poults, respectively, because of an increase in the concentration of malted sorghum in chicken diets. The reason for such poor performance was attributed to the presence of tannin and non-starch polysaccharides (NSP) in the malted sorghum sprouts [19]. The above studies [17–19] did not specify what type of malted sorghum meal they investigated. The present study investigated the effects of malted sorghum meal from red and white varieties on the performance of broilers.

It is known that red sorghum contains more tannin than white sorghum [20], which may explain the current results on HCW, CCW, HCY, and dressing out percentage, whereby broilers fed on white sorghum-based diets performed better than those fed red sorghum-based diets. The reason why hot carcass weight, cold carcass weight, hot carcass yield and dressing out percentage were low in broilers fed malted sorghum-based diets could be due to the increased partitioning of energy to the gastrointestinal organs (i.e., gizzards and large intestine) and other internal organs (i.e., liver and heart), consequently increasing the heat increment and the total cost of maintenance in broilers fed these diets. These are relatively energetically active organs and their growth results in an increase in heat production, and consequently reduces the energy needed for production (NEp) [21,22]. However, these results contradict the findings by Yaşar et al. [23], who observed that broiler broilers fed fermented cereals (barley, wheat and oats) produced higher carcass yields than those fed unfermented cereals.

In the present study, broilers fed malted sorghum-based diets had heavier wings, TDW, and TDWR, but it is not clear how wings, TDW, or TDWR were favoured under the present feeding regime that included malted sorghum meal. Similar reports [24,25] have reported higher mean wing and TDW in broilers fed fermented diets. Broilers in the current study fed malted sorghum diets had lower and/or similar breast weight, implying that there was a re-direction in the partitioning of nutrients away from the breast muscle, perhaps to other parts of the body such as the wings, thigh–drumsticks, and gastrointestinal organs.

The biological criteria for the discriminatory partitioning of nutrients to different organs are not understood in the present study. Similarly, Zhai et al. [25] found no significant differences in the breast weight of ducks fed fermented liquor distiller's grains. The pH_u was within a normal range (5.5–6.5) for chickens [26], suggesting that the inclusion of malted sorghum in a broiler diet did not affect glycogen levels. The pH range is an indication of how much glycogen was in the breast muscle prior to slaughter, and how rapidly the remaining glycogen was converted to lactic acid after slaughter [27].

It is known that feeding high fibrous diets increases the volume of GIT and organ development in chickens, ducks, and geese [28]. This explains why broilers fed the malted sorghum diets had longer large intestines, heavier livers, gizzards and hearts. The enlargement of the organs is an adaptive mechanism to deal with high amounts of fibre [29,30] in a monogastric animals. The crude fibre of malted sorghum was found to be 28.6% [31], while [13] recorded NDF concentration in malted Segaolane to be 52.3%. These results are supported by studies in the literature [30,32] who reported enlarged and thicker intestines in broilers fed diets with high fibre.

The liver detoxifies any toxins in the diet, and in the present study the larger livers of broilers fed MRSBD could have been triggered by a high concentration of tannin or other anti-nutrients in the MRSBD. In contrast, Silva et al. [33] observed higher relative liver weights when ground maize was fed compared to ground sorghum. In another study, Ahmed et al. [34] observed that the replacement of maize with 100%, 75%, 50%, 25%, and 0% sorghum in broiler diets did not show any significant effects on liver weights. Since the study by Ahmed et al. [34] did not specify the type of the sorghum (i.e., red or white) or processing (malting/fermenting or not), it would be difficult to tell if anti-nutrients, especially tannins, were absent or not.

In a recent study, Al Mashhadani and Al-Rubaie [35] found that, in Ross 308 broiler chicks fed from age 0 to 10 days, raw or germinated red sorghum did not elicit a difference in performance, while at age 11 to 24 days, raw red sorghum resulted in superior body weight and weight gain compared to the germinated red sorghum diet. These conflicting results from various studies point to differences in the composition of, processing of, and rate of feeding of sorghum, as well as the rearing environment and management of broilers.

In our unpublished research [31], it has been observed that the malting of sorghum does not completely remove condensed tannin, and hence the liver may be over-worked to detoxify phyto-chemicals [30]. Generally, an increase in liver and heart size could be indicative of the need to deal with toxic substances in the feed. Larger gizzards could be explained by the higher structural wall components of malted sorghum meal (28.6% crude fibre reported by Moses et al. [31] or course particles in the diet, causing the gizzard muscle to enlarge as an adaptive measure to create a suitable texture for digestion. Similar results were reported by Manyelo et al. [36], who found heavy gizzard weights in broiler chickens fed 75% and 100% sorghum-based diets.

The similar length of the small intestine (SI) and caeca of all broilers across the experimental diets implies that the crude fibre contents may have been effectively digested prior to arriving at the SI and caeca, curtailing the accelerated development of these organs. This finding is in line with a study by Silva et al. [33], who compared ground maize, sorghum, and whole-grain sorghum in broilers and found similar SI and caeca across the treatment diets. Similarly, the graded level of white sorghum meal did not result in any difference in the weights of the liver or intestine, or the intestinal length when included in the broiler chicken diets to replace maize [37]. However, Manyelo et al. [36] indicated that longer small intestines in broiler chickens are associated with a strategy to provide a greater surface area for nutrient absorption.

The excess supply of carbohydrates and proteins in the diets would be stored as crude fat in the muscle [38]. It is, therefore, not surprising that in the present study lower crude fat was found in the breast muscle of broilers fed MRSBD. This could be due to the efficient utilization of nutrients due to the antioxidant characteristics of the diets, such as the lowering of cholesterol and other fatty acids. Indeed, Saleh et al. [39] noted that feeding low-tannin sorghum decreased plasma triglycerides and total cholesterol concentration in broilers. Similarly, Marcinčák et al. [40] found that the breast muscle of Cobb 500 broilers fed with cornmeal fermented with filamentous fungi *Umbelopsis isabellina* had lower crude fat content when compared to the commercial diet.

Recent research [39] investigating the effect of substitutions of yellow corn diets with low-tannin sorghum on growth performance, plasma lipid profile, and gene-expression-related growth and antioxidative properties in broiler chickens recorded positive results for the metabogenomics of chickens. The mRNAs of genes related to growth and antioxidative properties, insulin growth factor (IGF), β-actin, fatty acid synthesis (FAS), glutathione peroxidase (GPX), and superoxide dismutase (SOD) were significantly increased due to low-tannin sorghum substitutions [38], implying health benefits to the birds. Thus, the results from the current study imply that malted sorghum-based diets reduce the fat content in chicken breast muscle, which is a good meat attribute, since the high consumption of fat is associated with nutritional diseases such as high blood pressure and obesity in consumers.

As for the other parameters, the lack of difference in the dry matter, ash, organic matter, energy, crude fibre, and crude protein content of the chicken muscle was in line with a study by Kim and Kang [41] who investigated the effects of diets containing fermented barley or wheat on the proximate analysis of the breast meat of broilers and did not notice any differences. This implies that malting did not lower or change the quality of the meat of the broiler chickens in relation to the yellow maize diet, and thus could be used as a substitute for yellow maize in broiler diets.

The challenge of mineral nutrition in sorghum diets is unavailability due to anti-nutrients, i.e., tannin, phytic acid, oxalate, polyphenol, and trypsin inhibitors [42]. However, as in contemporary Australian sorghum crops, Botswana white varieties such as BSH1, Mmabaitse, Segaolane, and Phofu [9,10] almost certainly have no or little tannin; nevertheless, the likelihood is that other "non-tannin" phenolic compounds may negatively influence energy utilization [43] and certain minerals. The observation that malted sorghum diets had lower muscle P contents as compared to the control could be due to the lower concentration and/or supply of this mineral from the experimental diets.

The breast muscle of the broilers fed MWSBD had low Ca and Na contents, which could be due to the antagonistic relationship with other minerals or anti-nutrients such as phytic acid, leading to the poor absorption of minerals from the diet. Phytic acid was not quantified in this study, but our laboratory previously recorded 11 and 17% differences between malted and un-malted sorghum grains for tannins in red and white sorghum types, respectively [31]. Indeed, Al-Yasiry et al. [44] reported a relationship between fat and calcium level in the muscle. A high calcium level is usually accompanied by a reduced fat content in meat [45].

The broilers fed MSBD had higher contents of K and Mg in their muscle, suggesting the availability of these minerals in the malted sorghum grains and the ability of the chickens to absorb and utilize them. Additionally, these results are supported by Mohammed et al. [46], who reported that, generally, sorghum grains contain a higher concentration of K but red sorghum contains higher K than white and yellow sorghum.

5. Conclusions

The results from this study reveal that carcass characteristics, viscera macromorphometry, and meat quality from the carcasses of broilers fed MWSBD or MRSBD compared well to those fed the control diet. It can be concluded that malted sorghum grains have the potential to be used to replace maize in broiler diets without having adverse effects on carcass characteristics, viscera macromorphometry parameters, or the meat quality traits of chickens. This was more pronounced in meat cuts which happen to be popular with customers.

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