frontiers | Frontiers in Animal Science

TYPE Original Research
PUBLISHED 16 February 2026
DOI 10.3389/fanim.2026.1747486

OPEN ACCESS

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RECEIVED 16 November 2025
REVISED 07 January 2026
ACCEPTED 21 January 2026
PUBLISHED 16 February 2026

CITATION
Sebola NA (2026) Effects of substituting maize with sorghum and soybean meal with canola meal on the growth performance, blood parameters, and organoleptic quality of rabbits according to sex. *Front. Anim. Sci.* 7:1747486.
doi: 10.3389/fanim.2026.1747486

Effects of substituting maize with sorghum and soybean meal with canola meal on the growth performance, blood parameters, and organoleptic quality of rabbits according to sex

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Increasing volatility in the cost and supply of maize and soybean meal necessitates the evaluation of locally available alternatives such as sorghum grain and canola meal, yet their combined effects on growth performance, carcass traits, serum biochemistry, and meat quality of grower rabbits, particularly in relation to sex remain inadequately documented. This study evaluated the impact of completely substituting maize with sorghum and soybean meal with canola meal on the growth performance and carcass characteristics of grower rabbits, while also examining whether sex interacts with these dietary changes to influence serum biochemical parameters and organoleptic meat quality. Forty rabbit weaners (20 bucks and 20 does; 6.13 ± 6.59 g live weight) at one month of age were randomly allocated to two dietary treatments in a two-way factorial arrangement (diet × sex) under a completely randomized design. Each rabbit was housed individually in a 0.07 m^2 pen, with five replicates per treatment. Two iso-nitrogenous and iso-energetic diets were formulated: a maize–soybean-based commercial grower diet (control) and an experimentally formulated sorghum–canola meal (SCM) diet in which sorghum fully replaced maize and canola meal replaced soybean meal. Rabbits fed the SCM diet exhibited significantly higher (P < 0.05) body weight gain, improved carcass traits, and superior meat quality compared with those on the control diet. Does gained more weight than bucks (P < 0.05), regardless of diet. Rabbits on the SCM diet had higher (P < 0.05) plasma sodium concentrations; however, sex had no significant effect on serum biochemical parameters or sensory meat quality, and no diet × sex interaction was observed. These findings indicate that complete replacement of maize and soybean meal with sorghum and canola meal can enhance growth performance without adverse effects on physiological status or meat quality, irrespective of sex. Sorghum and canola meal therefore represent viable, sustainable, and cost-effective alternatives for rabbit production systems.

KEYWORDS

blood parameters, canola meal, grower diet, growth performance, organoleptic quality, rabbit, sex, sorghum

Introduction

Rabbit production holds considerable potential to address the nutritional needs of resource-limited communities, thereby supporting sustainable food and nutrition security. In South Africa, the commercialization of rabbit farming gained momentum shortly after World War II, primarily for the production of high-quality meat (Steenekamp, 2023). Rabbit meat is well recognized for its superior nutritional profile, being rich in high-quality protein yet low in fat and cholesterol, making it an appealing option for health-conscious consumers (Mutsami and Karl, 2020).

Globally, intensive rabbit production has expanded rapidly in countries such as Italy, China, Korea, Spain, and Egypt, driven by the species' favorable biological traits, including rapid growth, early maturity, high fecundity, and the capacity to thrive on grain-free diets (Patricci et al., 2009; Trocino et al., 2019). Despite these advantages, the intensification of rabbit production remains constrained by the high cost of feed, particularly energy- and protein-rich ingredients such as maize and soybean meal. These conventional feedstuffs are expensive and highly competitive, as they serve multiple roles in human food systems and industrial applications (Tenenbaum, 2008). In addition, the large-scale cultivation of maize and soybeans often involves deforestation, intensive irrigation, and heavy use of synthetic fertilizers and agrochemicals, which contribute to environmental degradation and rising production costs. In light of these challenges, it is imperative to identify and evaluate alternative, cost-effective dietary energy and protein sources that do not compete with human consumption or industrial uses. Such alternatives could play a crucial role in reducing feed costs and enhancing the sustainability and profitability of rabbit farming systems. Sorghum (*Sorghum bicolor* Moench L.) and canola meal have emerged as viable alternatives that can either fully or partially replace soybean meal and maize in commercial rabbit diets, respectively.

Sorghum is a drought-tolerant crop that thrives under harsh conditions and possesses a nutrient composition comparable to that of maize, with a slightly higher protein content (Walker, 1999; Farahat et al., 2020). Canola meal, a by-product of oil extraction, provides substantial protein levels (36%–39%) and an amino acid profile similar to that of soybean meal (Manyeula et al., 2020), making it suitable for inclusion in monogastric diets. Although both ingredients contain antinutritional factors (ANFs), such as tannins, phytates, and glucosinolates (Wiryawan and Dingle, 1999; Liu et al., 2015), advances in plant breeding have significantly reduced their concentrations, thereby improving their feed value. Moreover, the rabbit's gastrointestinal tract is well adapted to high-fiber diets, enhancing its ability to utilize such ingredients efficiently (Gidenne, 2003).

Previous research has explored the use of sorghum and canola meal in the diets of rabbits, broilers, and quails (Mohammed et al., 2017; Disetlhe et al., 2018; Mabelebele et al., 2019; Manyeula et al., 2019; Masenya et al., 2021). However, studies assessing the complete replacement of maize and soybean meal with sorghum and canola meal remain limited. Especially in both rabbit bucks and does, these animals differ in feed utilization. Therefore, testing this diet in both sexes is necessary to guarantee that the outcomes are representative of the total population. It was hypothesized that total replacement of maize and soybean meal with sorghum and canola meal, respectively, would enhance growth performance, serum metabolites, and meat quality in both male and female rabbits. Therefore, the present study aimed to evaluate the effects of substituting maize with sorghum and soybean meal with canola meal in rabbit diets, while examining the influence of sex on growth performance, serum biochemical parameters, carcass characteristics, and organoleptic quality.

Materials and methods

Ethical statement, source of ingredients, and study location

This study was conducted during the summer season (25°C–35°C range) at Kaffirstad Farm (Mpumalanga Province, South Africa), situated at 26.34°S and 29.18°E. Sorghum (Table 1) was acquired from the Agricultural Research Council (Potchefstroom, South Africa). SBM, corn, molasses, lime, and premix were obtained from Opti Feeds (Lichtenburg, South Africa), while canola meal was purchased from Southern Oil (Pty) Ltd., South Africa.

Experimental diets and chemical analysis

Two iso-nitrogenous and iso-energetic treatment diets were formulated as follows: 1) a maize–soybean diet = control diet; and 2) a sorghum–canola meal (SCM) diet totally replacing maize with sorghum and soybean with canola meal in rabbits' diets (Table 1), to meet the nutritional requirements recommended by the National Research Council (NRC, 1977). Experimental diets were milled and analyzed for dry matter, organic matter, and crude protein, as per method nos. 930.15, 924.05, and 984.13, respectively (AOAC, 2005), while crude fiber (ANKOM Technology, New York, USA) and minerals (calcium, phosphorus, sodium, chloride, and potassium) were analyzed in accordance with the AgriLasa (1998) guidelines.

House preparation, feeding trial, and management of rabbits

Thorough cleaning of the house and equipment was done with water and detergent. Thereafter, disinfection was done with F10 (Health and Hygiene (Pty) Ltd., Roodepoort, South Africa). After a 2-week downtime, the house was warmed using an infrared bulb, prior to commencing the experiment. A total of 40 New Zealand white rabbits (20 bucks and 20 does), with an average initial weight of 613 ± 6.59 g, were randomly allotted to two treatment diets in a two-way factorial arrangement in a CRD with a pen (0.07 m^2 per weaned rabbit) as an experimental unit, holding one rabbit,

TABLE 1 Ingredients and chemical composition of experimental diets (g/100 g DM).

	Experimental diets[1]			
	CON	SCM	Sorghum	Canola meal
Ingredients				
Corn	38	0		
White sorghum	0	37		
Canola meal	0	16.5		
Hay	42	42		
Soybean	17	0		
Molasses	1.5	1.5		
Limestone	1.0	2.5		
Premix	0.5	0.5		
Total	100.0	100.0		
Chemical analysis	0	5		
Moisture	9.91	10.58	13.7	7.0
Crude protein	13.49	13.28	12.4	34.4
Ether extract	3.62	5.19	8.1	23.0
Crude fiber	21.87	21.23	2.9	2.4
Ash	5.31	5.28	10.4	7.0
Energy (MJ/kg)	12.1	11.9	16.8	17.6

[1]Experimental diets: CON = maize–soybean meal diet; SCM = sorghum–canola meal diet.

replicated five times. The house was fitted with an automatic nipple drinker, while feed was offered *ad libitum*, with constant lighting (24 h) for a period of 42 days.

Growth performance, blood collection, and analysis

Every morning, feed was offered, and refusals were weighed using a digital weighing scale (Explorer EX224, 0.01g, OHAUS Corp., Parsippany, NJ, USA). All the rabbits were weighed for initial weight at the start of the experiment, and thereafter on a weekly basis, to determine weekly weight gain (WWG). The feed conversion ratio (FCR) was then computed as the average feed intake (FI) over average weight gain. During slaughtering, blood was collected from three rabbits randomly selected from each treatment and sex from the neck, into a 4-mL red top anticoagulant, then stored for 45 min at room temperature to coagulate, before being refrigerated at 4°C (Washington and Van Hoosier, 2012). Next, 48 h after blood collection, serum was made by centrifuging the clotted blood for 20 min at 1,500 rpm. The serum supernatant settled on top, while blood cells were deposited at the bottom. The serum was sieved into a 0.5-mL conical centrifuge tube and then stored at −20°C. Finally, the serum biochemical parameters (total protein, albumin, creatine, urea, sodium, potassium, calcium, magnesium, glucose, cholesterol, triglycerides, alanine transaminase, and aspartate aminotransferase) were analyzed using an automated Idexx Vex Test Chemistry Analyser (IDEXX Laboratories, Inc., Westbrook, ME, USA).

Slaughter protocol

All rabbits were starved for 13 h at the end of the feeding trial, then weighed (slaughter weight) using a digital weighing scale, and transported to a local poultry abattoir for slaughtering. The rabbits were electrically stunned and hung upside down on a movable metal rack. The jugular vein was cut with a sharp knife for bleeding, and they were then skinned.

Meat color and pH measurement

Muscle color was determined 24 h after slaughter. The fillet and leg color, including lightness (L*), redness (a*), and yellowness (b*), were determined by a spectrophotometer (CM 2500c model, Konica Minolta, Japan), replicated three times to obtain the average value of the color. A pH meter (CRISON pH25, CRISON Instruments SA, Spain) was used to determine the pH of each rabbit at 45 min (pH_i) and 24 h (pH_u) post-mortem, as described by Manyeula et al. (2020).

Drip loss

From the 24 sampled rabbits (12 males and 12 females), approximately 30 g of muscle strips were cut from the fillet muscle, parallel to the fiber direction, then weighed (W_i) on a weighing scale (Explorer EX224, OHAUS Corp.) of 0.01 g sensitivity. The muscle strips were suspended in a cold room (4°C) for 72 h and reweighed (W_F) to determine drip loss, following the method proposed by Honikel and Hamm (1994), as indicated in Equation 1:

$$Drip\ \ loss = \frac{W_F - W_i}{W_i} \times 100 \tag{1}$$

Cooking loss

Raw muscle cubes from 24 sampled rabbits were cut from the fillet muscles, initially weighed (W_i), and oven-heated at 75°C for 45 min. Thereafter, the oven-heated muscle was cooled down at room temperature for 15 min and dried with soft tissue and reweighed (W_F) (Sanka and Mbanga, 2014). Cooking loss was calculated using Equation 2:

$$Cooking\ \ loss = \frac{W_{F-W_I}}{W_F} \times 100 \tag{2}$$

Sensory evaluation

A total of 50 untrained consumers were recruited from among the participants in a 1-day conference held at the North-West University (Mafikeng, North-West Province, South Africa). Information regarding sensory evaluation was collected via a questionnaire before the sensory assessment of the samples, which was conducted in the class, before lunch at noon. Each individual panelist was issued with an eight-point hedonic scale to evaluate each meat sample from the two treatments and deionized water to cleanse the mouth after each sample was offered. Verbal instructions on the test were highlighted prior to commencing. Approximately 5-cm portions of meat were cut and baked for 30 min in an oven (105°C). Immediately after cooking, the meat was cut into 1 cm^3, randomly placed (one/treatment) on a plastic form pack, and divided into two equally sized wedges. Each panelist assessed two samples, one from each of the dietary treatments, and numbers were used to identify the samples. The panelists were asked to score each sample using an eight-hedonic scale, as follows: extremely bland = 1; very bland = 2; fairly bland = 3; slightly bland = 4; slightly intense = 5; fairly intense = 6; very intense = 7; and extremely intense = 8, following the procedure proposed by William et al. (2023).

Statistical analysis

The data on average weekly weight gain were analyzed using repeated measures analysis (SAS, 2010), employing the following statistical model:

$$\gamma_{ijkl} = \mu + D_i + S_j + W_k + (D{*}S)_{ij} + (D{*}W)_{ik} + E_{ijkl}$$

Where, Y_{ijkl} = respond variables, μ = population mean, D_i = effects of diets, S_j = effects of sex, W_k= time effect in week, $(D{*}s)_{ij}$ = interaction effect (diet and sex), $(D{*}W)_{ij}$ = diets and weekly interaction effect, and E_{ijkl} = random error.

Overall growth performance, serum parameters, and meat quality data were analyzed using the general linear model (GLM) procedure of the Statistical Analysis System (SAS, 2010), with the dietary treatment and sex as the factors, using the model below:

$$\gamma_{ijk} = \mu + D_i + S_j + (D{*}S)_{ij} + E_{ijK}$$

Where, γ_{ijk} = dependent variable, μ = population mean, D_i= diets effect, S_j = Sex effect, DS_{ij} = interaction of diet and sex, and E_{ijk}= random error associated with observation, ij = assumed to be normally and independently distributed. Significance was declared at $P \le 0.05$, and the means were separated using the probability of difference option in the LSMEANS statement of SAS.

Results

Growth performance

The main rabbits' performance parameters, with values of FI, FCR, and AWG, are summarized in Table 2. They showed that there was a diet and sex (male or female) interaction ($P < 0.05$) effect

TABLE 2 Overall feed intake and feed conversion ratio of rabbits, as affected by the main effects (diet and sex) and their interaction.

Parameters	Diet[1]		Sex[2]			Main effects		
	CON	SCM	♂♂	♀♀	SEM	Diet	Sex	Interaction
Feed intake (g/rabbit)	94.6	92.9	91.9	95.5	1.09	NS	NS	NS
Average weight gain	23.0[b]	34.4[a]	29.3	32.5	4.2	*	NS	*
Feed conversion ratio	3.9	3.5	4.0	3.36	0.31	NS	NS	NS

NS, not significant; SEM, standard error of the mean.
[1]Diets: CON = commercial rabbit grower diets; SCM = total replacement of maize with sorghum and soybean with canola meal in rabbits' diets.
[2]Sex: ♂♂ = males; ♀♀ = females.
*$P < 0.05$.
a, b: Mean on the same row with different superscripts differ significantly ($p < 0.05$).

on AWG (P = 0.01) but not on FI (P = 0.96) and FCR (P = 0.89). Likewise, significant diet was also noted on AWG (P = 0.03), but not on FI (P = 0.98) and FCR (P = 0.36). Diet and sex did not affect overall FI and FCR but influenced overall weight gain.

In weeks 3 and 6, only the diet had significant effects (Table 3). However, in weeks 4 and 5, the effects (P < 0.05) were on diet and sex only, whereas in weeks 7 and 8, only sex had a significant effect. Rabbits fed SCM were the heaviest in weeks 1, 3, 4, 5, and 6. In week 1, the bucks were heavier (P < 0.05) than the does, whereas in weeks 4, 5, 7, and 8, the opposite was true. No significant effects, based on sex, were detected in weeks 2 and 6.

Blood biochemical parameters

The findings in Table 4 showed that the diet significantly affected sodium and potassium, while magnesium was affected by both diet and interaction. Protein, creatinine, and cholesterol were significantly affected (P > 0.05) by interaction (diet * sex). With regard to diet effects, potassium and magnesium were higher in rabbits fed the CON diet, compared to those on the SCM diet, whereas sodium was higher in the rabbits reared on the SCM diet than those on the CON diet. Sex did not have any significant effect (P > 0.05) on the plasma protein, minerals, energy, and enzyme profiles of the rabbits.

Physicochemical characterization

The interaction (diet * sex) was significant on leg b*, pH_u, and drip loss compared with the other experimental groups (Table 5). Fillet L* and b*, pH_u, cooking, and drip loss were affected by the diet, whereas sex affected (P < 0.05) pH_u and drip loss only in terms of meat quality. Rabbits fed the SCM diet had the highest fillet L*, b*, and pH_u, while those fed the control diet had the highest values on cooking and drip loss. Nonetheless, sex significantly affected pH_u and drip loss only (Table 5). Other meat quality parameters were not significantly (P > 0.05) affected by the main effects. Does recorded the highest value of pH_u but had the lowest value of drip loss.

Carcass traits and internal organs

There was no diet and sex (male or female) interaction in the heart, liver, kidneys, lungs, and small intestine (Table 6). Likewise, no significant dietary effects were observed on the fillet, heart, kidney, lungs, and small intestines. Notably, sex significantly affected the hot carcass weight (HCW), cold carcass weight (CCW), hind legs, heart, liver, and large intestine (Table 6). Rabbits fed the SCM diet had the highest values (P < 0.05) of HCW, CCW, hind leg, heart, liver, and large intestine weights. Does had significantly higher HCW, CCW, and hind leg weight. On the other side, the liver and large intestine weights were higher (P < 0.05) in bucks, while other parameters were not affected.

Sensory attributes

Table 7 shows that diet did not affect (P > 0.05) meat quality. The consumers classified the meat from rabbit-fed treatment diets as slightly intense in all attributes.

Discussion

Growth performance

Sorghum offers a nutritive value comparable to that of maize and other conventional feed grains, confirming its suitability as a feed ingredient (Zarei et al., 2022). Similarly, canola meal ranks second only to soybean meal as a high-quality protein source in

TABLE 3 Means of body weight gain (g/rabbit) in subsequent weeks of rabbit growth in grams, as affected by the main effects (diet and sex) and their interaction.

Age	Diet[1]		Sex[2]			Main effects		
	CON	SCM	♂♂	♀♀	SEM	Diet	Sex	Interaction
Week 1	19.0^b	49.3^a	37.5^a	30.1^b	2.09	*	*	*
Week 2	24.9	45.3	28.9	41.4	7.14	NS	NS	NS
Week 3	15.7^b	20.9^a	18.3	18.3	1.35	*	NS	NS
Week 4	24.6^b	39.2^a	24.5^b	39.3^a	1.68	*	*	NS
Week 5	20.4^b	36.1^a	22.5^b	34.1^a	3.26	*	*	NS
Week 6	25.4^b	31.1^a	29.2	27.3	0.64	*	NS	NS
Week 7	27.7	31.1	23.6^b	35.3^a	1.39	NS	*	NS
Week 8	26.5	26.3	24.2^b	28.6^a	0.84	NS	*	NS

NS, not significant; SEM, standard error of the mean.
[1]Experimental diets: CON = commercial rabbit diet; SCM = total replacement of maize with sorghum and soybean with canola meal in rabbit diets.
[2]Sex: ♂♂ = males; ♀♀ = females.
*P < 0.05. a, b: Mean on the same row with different superscripts differ significantly (p < 0.05).

TABLE 4 Blood biochemical parameters (mmol/L, unless otherwise stated) in rabbits as affected by the main effects (diet and sex) and their interaction.

Parameters	Diet[1]		Sex[2]			Main effects		
	CON	SCM	♂♂	♀♀	SEM	Diet	Sex	Interaction
Plasma protein profile (μmol/L)								
Total protein	54.9	60.8	60.6	55.1	2.24	NS	NS	*
Albumin	46.2	44.2	50	40.4	4.62	NS	NS	NS
Creatinine	62.2	57	57.9	61.3	2.6	NS	NS	*
Urea	0.3	0.06	0.1	0.2	0.22	NS	NS	NS
Plasma mineral profile								
Sodium	136.8^{b}	141.0^{a}	139.5	138.3	1.22	*	NS	NS
Potassium	6.0^{a}	4.6^{b}	5.4	5.3	0.38	*	NS	NS
Calcium	3.2	3.3	3.3	3.2	0.06	NS	NS	NS
Magnesium	1.9^{a}	1.6^{b}	1.8	1.6	0.07	*	NS	*
Plasma energy profile								
Glucose	5.6	5.4	5.3	5.6	0.32	NS	NS	NS
Cholesterol	1.8	1.6	1.7	1.7	0.12	NS	NS	*
Triglycerides	1	1	0.9	1.1	0.01	NS	NS	NS
Plasma enzyme profile (IU/L)								
Alanine transaminase	39.7	41.7	42.1	39.2	2.93	NS	NS	NS
Aspartate aminotransferase	61.6	61.3	65.3	57.7	8.61	NS	NS	NS

NS, not significant; SEM, standard error of the mean.
[1]Diets: CON = commercial rabbit grower diets; SCM = totally replacing maize with sorghum and soybean with canola meal in rabbit grower diets.
[2]Sex: ♂♂ = males; ♀♀ = females.
*$P < 0.05$. a, b: Mean on the same row with different superscripts differ significantly ($p < 0.05$).

TABLE 5 Meat quality parameters in rabbit meat as affected by diet, sex, and their interaction.

Parameters	Diet[1]		Sex[2]			Main effects		
	CON	SCM	♂♂	♀♀	SEM	Diet	Sex	Interaction
Fillet color								
L* (lightness)	47.6^{b}	48.5^{a}	45	47.3	1.16	*	NS	NS
a* (redness)	10.7	11.4	11.1	11.6	0.26	NS	NS	NS
b* (yellowness)	10.1^{b}	12.7^{a}	11	11.7	0.51	*	NS	NS
Leg color								
L* (lightness)	47	48.8	47.7	48.1	1.21	NS	NS	NS
a* (redness)	11.1	11.8	11.6	11.3	0.34	NS	NS	NS
b* (yellowness)	12.8	11.3	12.2	11.9	0.67	NS	NS	*
pH_i	7.2	7.3	7.1	7.4	0.14	NS	NS	NS
pH_u	6.9^{b}	7.1^{a}	6.4^{b}	7.1^{a}	0.03	*	*	*
Peak force	0.5	0.5	0.6	0.4	0.05	NS	NS	NS
Cooking loss	39.9^{a}	26.3^{b}	34.8	31.3	2.67	*	NS	NS
Drip loss	59.0^{a}	53.1^{b}	60.9^{a}	51.2^{b}	1.42	*	*	*

NS, not significant; SEM, standard error of the mean.
[1]Diets: CON = commercial rabbit diet; SCM = total replacement of maize with sorghum and soybean with canola meal in rabbit diets.
[2]Sex: ♂♂ = males; ♀♀ = females.
*$P < 0.05$. a, b: Mean on the same row with different superscripts differ significantly ($p < 0.05$).

TABLE 6 Carcass characteristics and internal organs (% of HCW, unless otherwise stated) of rabbits, as affected by diet, sex, and their interaction.

Parameters	Diet[1]		Sex[2]			Main effects		
	CON	SCM	♂♂	♀♀	SEM	Diet	Sex	Interaction
HCW	933.0^{b}	1,037.7^{a}	946.0^{b}	1,074.7^{a}	19.52	*	*	*
CCW	881.7^{b}	1,033.3^{a}	894.0^{b}	1,025.0^{a}	19.48	*	*	*
Fillet legs	7.1	6.9	6.5^{b}	7.5^{a}	0.11	*	NS	*
Hind legs	0.1^{b}	0.1^{a}	0.1^{b}	0.1^{a}	0.002	*	*	*
Fillet	5.3	5.3	4.9	5.6	0.23	NS	NS	*
Heart	0.4^{b}	0.5^{a}	0.5	0.4	0.03	NS	*	NS
Liver	4.2^{b}	5.6^{a}	5.3^{a}	4.5^{b}	0.23	*	*	NS
Kidneys	0.7	0.7	0.7	0.7	0.04	NS	NS	NS
Lungs	1.4	1.4	1.6	1.3	0.13	NS	NS	NS
SI (mm)	3,425.00	3,000.00	3,176.10	3,248.30	153.1	NS	NS	NS
LI (mm)	504.2^{b}	576.2^{a}	585.0^{a}	443.0^{b}	21.91	*	*	*

[1]Diets: CON = commercial rabbit diet; SCM = total replacement of maize with sorghum and soybean with canola meal in rabbit diets.
[2]Sex: ♂♂ = males; ♀♀ = females.
HCW, hot carcass weight; CCW, cold carcass weight; SI, small intestine; LI, large intestine; SEM, standard error of the mean; NS, not significant.
*P < 0.05. a, b: Mean on the same row with different superscripts differ significantly (p < 0.05).

animal diets and is rich in essential minerals, vitamins, and beneficial phenolic compounds (Newkirk, 2009). In this study, previous results showed that the interaction (diet * sex) affected weight gain, suggesting that the weight gain of rabbits is affected by age and sex. A lack of interaction (diet * sex), observed in Tables 2-6, indicates that diet and sex acted independently on those parameters. However, significant interaction in the tables revealed that those parameters were acted on jointly by diet and sex. A lack of interaction effects (diet * sex) on FI concurs with the findings of Hussein and Abdelfattah (2020), who reported no interaction (diet * sex) in FI in growing rabbits fed a concentrate meal. The interaction (diet * sex) on FCR contradicts the findings of the study of Hussein and Abdelfattah (2020): diet and sex did not have effects on FI and FCR, implying that the feed was consumed and converted to muscle in the same way as in the control diet. This aligns with what was reported by Gugołek et al. (2018), who found similar FI and FCR in rabbits fed rapeseed meal, white lupine, and pea seeds as SBM substitutes. Also, Hussein and Abdelfattah (2020) reported that sex had no significant effect on the FI of California rabbits fed a commercial diet. The lack of significant diet and sex effects on FI suggests that substituting maize with sorghum and SBM with canola meal as energy and protein ingredients in rabbit diets does not change the palatability of the diets, irrespective of the sex of the animal. The non-significant interaction (diet * sex) on weight gain aligns with the findings of a study by North et al. (2018). Rabbits have been reported to possess well-developed GITs when it comes to utilizing fibrous diets and tolerating antinutritional compounds such as tannin (Wolf and Cappai, 2020). This may explain why rabbits fed SCM diets had similar (weeks 2, 7, and 8) or higher in other weeks in BWG, compared to those reared on the control diet. These observations match those of Njoku et al. (2013), who reported an increased average daily weight gain with increasing sorghum milling dust in the diets of growing rabbits. Indeed, it was noted by Hamlin (2012) that rabbits are anatomically and physiologically developed for a high-fibrous (20%–25%) diet. The faster weight gain of does (more than bucks) in week 1 was surprising, and there is no evidence as yet to show that this was reported in previous rabbit- or livestock-related research. The current results in weeks 4, 5, 7, and 8 match what is reported in the literature (Ologbose et al., 2017; Lamptey et al., 2022), where bucks were reportedly slightly heavier than does at all ages, possibly due to better feed utilization. Contrary to these results, Birolo et al. (2020) reported similar weights in male and female rabbits, in line with the results from weeks 2, 3, and 6, suggesting that in those

TABLE 7 Descriptive statistics for organoleptic quality of meat from rabbits fed diets containing sorghum as maize substitute and canola meal as soybean substitute in rabbits' diets.

Attributes	Diets[1]			Significance
	CON	SCM	SEM	
Aroma	5.4	5.5	0.29	NS
Juiciness	4.8	5.3	0.31	NS
First bite	5.5	5.6	0.32	NS
Sustained juiciness	5.2	5.5	0.27	NS
Overall tenderness	5.4	5.5	0.27	NS
Connective tissue	4.5	5.0	0.29	NS
Flavor overall	5.2	5.2	0.27	NS
Typical flavor	4.8	5.4	0.30	NS

SEM, standard error of the mean; NS, not significant.
[1]Diets: CON = commercial rabbit diet; SCM = total replacement of maize with sorghum and soybean with canola meal in rabbit grower diets.

weeks rabbits utilized feeds to the same degree of efficiency, regardless of their sex. This could be because, 6 weeks after weaning, bucks and does frequently use diets similarly because they have not reached sexual maturity, when physiological and metabolic disparities depending on sex become more noticeable.

Blood biochemical parameters

Interaction (diet * sex) was observed on protein, creatinine, magnesium, and cholesterol, suggesting that these serum metabolite parameters are controlled jointly by diet and sex. The plasma proteins and energy were not affected by diets and sex, suggesting that the intake of the sorghum–canola-based diet had no negative post-ingestive feedback, irrespective of sex. The lack of post-ingestive feedback was further explained by similar (P < 0.05) plasma enzymes (ALT and AST) profiling, which are indicators of hepatocellular damage (Ambrosy et al., 2015), and suggests that the combination of sorghum and canola has the potential to be used in the diets of rabbits, as indicated by values falling within the normal ranges for healthy rabbits (Jenkins, 2008). The higher plasma sodium in rabbits reared on an SCM diet may be a reflection of the high concentration of this mineral reported in sorghum (9.04 mg/100 g), compared to maize (3.74 mg/100 g) (Jocelyne et al., 2020). Rabbits are more tolerant of high sodium, but a plasma sodium concentration above 185 mmol/L can induce hypernatremia (Patson and Sladky, 2020), which is why rabbits fed SCM did not show any sign of hypernatremia at plasma concentrations of 141.0 mmol/L in this study. Sorghum contains antinutritional factors such as tannins, kafirin, ferulic acid, endosperm, and phytate that hinder its utilization by monogastric animals and result in a lowering of the digestibility of carbohydrates, proteins, and minerals (Masenya et al., 2021), which could explain why rabbits fed a sorghum–canola-based diet had lower plasma potassium and magnesium levels. Moreover, canola is known to contain low levels of potassium and magnesium (Mahan et al., 2005).

Physicochemical characterization

Interaction (diet * sex) had significant effects on meat yellowness, pH_u, and drip loss, implying that these traits are controlled jointly by diet and sex, which contradicts the findings of the study of Daszkiewicz and Gugołek (2020). The decline in the pH value hinders the growth of undesired bacteria, rates of conversion of color, and the formation of undesired flavors in the meat, which was observed in the meat from rabbits reared on the CON diet in this study. It may be deduced that combining sorghum and canola in the diet of rabbits reduced the conversion rate of glycogen levels to lactic acid after slaughter, hence improving meat quality. This finding concurs with the literature reporting the effects of sorghum- (Hernández-Martínez et al., 2018) and canola-based diets (El-Medany and El-Reffaei, 2015) on the femoris and biceps muscles of rabbits. Investigators (Yalçın et al., 2006; North et al., 2018) reported higher muscle ultimate pH in bucks, whereas other studies found no sex-related effects on meat pH (Dalle Zotte et al., 2016; Frunza et al., 2019). Cooking and drip loss were higher in rabbits fed the control diet, which corroborates the findings reported by El-Medany and El-Reffaei (2015). Those authors reported significantly lower cooking loss in rabbits fed canola than in those fed a control diet. During meat processing (cooking and drying), juices are released together with the nutrients, due to protein denaturation and muscle atrophy (Purslow et al., 2016), resulting in poor-quality products. In this study, low cooking and drip loss observed in rabbits fed the SCM diet imply that utilizing sorghum and canola (SCM) in the diet improved the meat quality in terms of tenderness, juiciness, and flavor by promoting muscle structure to reduce the loss of juices (nutrients). Furthermore, drip loss can also be influenced by secondary metabolites (methylglyoxal), changing the properties of muscle proteins (Przybylski et al., 2022). Loss of water and the application of heat to the meat led to the formation of pores and shrinkage, which can affect the texture and taste, leading to poor meat quality (Koc et al., 2008). The significantly higher drip loss on the meat from does contradicted the findings of North et al. (2019), who reported similar drip loss values from the meat of males and females. The current results suggest that bucks possess better meat quality than does, as drip loss determines the appearance, texture, nutritional value, and attractiveness of the meat (Filho et al., 2016).

Carcass traits and internal organs

The heavier HCW, CCW, heart, hind leg, liver, and large intestine in rabbits reared on SCM could be associated with final weight. Indeed, Michalik et al. (2009) reported a strong positive relationship between rabbit body and carcass weight, which is indicative of an adequate diet and nutrition (Cardoso et al., 2011). However, the presence of toxins in the diet is reflected by hypertrophy or hypotrophy of the liver (Ewuola et al., 2003), which could be another reason why rabbits fed the SCM diet had heavier livers, as mentioned in the study of Masenya et al. (2021). The kidneys, heart, and large intestine were not affected by diet, suggesting that replacing maize with sorghum and canola with soybean in rabbit diets did not show any anatomical adaptation responses in the rabbits. The present results align closely with similar findings reported by many researchers (Hernández-Martínez et al., 2018; Wafar et al., 2020). The authors reported similar carcass traits and internal organs when weaner rabbits were fed a malted sorghum cultivar. In this study, it was clear that the sorghum–canola-based diet (SCM), when compared to the control diet, can improve the profitability of sustainable rabbit farming, as it is associated with heavier internal and external organs that determine market prices in the commercial milieu. The higher (P < 0.05) HCW, CCW, fillet, and hind leg weights of does contradict the findings of North et al. (2019), who found similar HCW, CCW, and hind leg weights in male and female rabbits. Bucks had heavier livers and hearts and longer large intestines than does, which correlate with the findings of Hussein and Abdelfattah

(2020), who reported significantly heavier internal organs in bucks than in does, which could explain why males grew faster than females (Hussein and Abdelfattah, 2020). The results reported by Tůmová et al. (2022) match the findings of the current study, i.e., the internal organ weights of rabbits were not affected by their sex.

Sensory attributes

The consumers classified the meat from rabbits fed with all treatment diets as slightly intense (5) in all attributes, implying that rabbit meat from an SCM diet would equally be patronized as the meat from rabbits fed the control diet. This indicates that the combination of sorghum (maize replacer) and canola (soybean replacer) in the rabbits' diet did not have an adverse effect on meat quality. However, meat juiciness is an important parameter for consumer choice, as it is associated with fat content (Wognin et al., 2018), and this led the researchers to deduce that the lack of a significant effect in this study could be due to similar lipid meat contents. Similar to these current results, Kpehe et al. (2020) reported a lack of difference ($P < 0.05$) in the organoleptic quality of the meat of rabbits fed diets containing graded levels of rice offal.

Conclusion

The total substitution of maize with sorghum, and soybean meal with canola meal, did not have any adverse effect on the growth performance, serum biochemical indices, and sensory evaluation of rabbits. A sorghum–canola-based diet has been found to promote weight gain. It can be concluded that sorghum–canola can be employed to substitute maize–soybean in rabbit diets.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

The animal study was approved by the University of Mpumalanga Research and Ethics Committee. The study was conducted in accordance with the local legislation and institutional requirements.

Author contributions

NS: Formal analysis, Methodology, Validation, Data curation, Project administration, Conceptualization, Software, Writing – review & editing, Funding acquisition, Investigation, Writing – original draft, Resources.

Funding

The author(s) declared that financial support was received for this work and/or its publication. This work was supported by the University of South Africa and Department of Agriculture and Animal Health.

Acknowledgments

Our thanks go to Opti Feeds (South Africa).

Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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