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Use of sunflower meal as a protein source in diets of growing lambs

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ABSTRACT - This study aimed to evaluate the effects of sunflower meal (SFM) inclusion on the performance, nutrient digestibility, and respirometric parameters in sheep. Twenty-four Dorper × Santa Inês uncastrated males, with an average age of 5 mo and initial body weight (BW) of 27.91±6.0 kg, were distributed in a randomized block design with four treatment diets containing 0, 100, 200, and 300 g of SFM/kg of total dry matter, replacing soybean meal. Intake, weight gain, ingestive behavior, and *in vitro* digestibility were evaluated according to the SFM inclusion. The respirometric parameters were evaluated in an open-circuit respirometric chamber. There was a quadratic response in dry matter intake expressed according to the SFM inclusion, with minimum points of 90.56 g/kg$^{0.75}$ BW for inclusion levels of 96 g of SFM/kg. A linear decrease in the *in vivo* digestibility of dry matter, neutral detergent fiber, and non-fibrous carbohydrate and *in vitro* fermentation of dry matter and fibrous carbohydrates was observed in response to SFM inclusion. These results reflect the higher fiber content of the byproduct, which reduced the non-fibrous carbohydrates in the diets. Despite the change in nutrient availability, average daily gain (299 g/day), O_2 consumption (26.24 L/kg$^{0.75}$ BW), and CH_4 production (2.25 L/kg$^{0.75}$ BW) were not influenced by the SFM inclusion, indicating that changes in the nutritional value of the diet did not affect the animals' energetic metabolism. Sunflower meal inclusion decreased the digestibility but did not affect the animal gain and the respirometric parameters. The SFM can replace soybean meal in the diet of growing lambs; however, it has a maximum inclusion point of 88 g SFM/kg for feed conversion, which is a necessary factor for evaluating the replacement cost.

Keywords: byproduct, energetic metabolism, *Helianthus annuus* L., lamb, ovine, respirometry

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1. Introduction

Sunflower (*Helianthus annuus* L.) oil extraction mainly produces meal and cake, which have strong potential for use in the feeding of ruminant animals (Goes et al., 2019; Monteiro et al., 2020; Vastolo et al., 2022). Sunflower byproducts comprise a protein source with high levels of essential amino acids, oleic and linoleic fatty acids, calcium, phosphorus, and B-complex vitamins (Nedelkov et al., 2021). Sunflower meal (SFM) has several advantages over other protein supplements, including a higher content of sulfur-containing amino acids, such as methionine, cystine, and cysteine (Nedelkov et al., 2021).

Sunflower meal composition varies greatly depending on the seed variety, soil characteristics, climatic conditions, peel removal, and oil extraction processing methods (Zagorakis et al., 2018; Nedelkov, 2019).

The crude fiber content varies from 12 to 32%, the crude protein (CP) content varies from 24 to 44%, and the ether extract (EE) content varies from 1 to 10% (Bonos et al., 2011). According to Liu et al. (2019), the net protein utilization of SFM (76.95%) is close to that of SBM net protein utilization (82.41%). Although it is a protein ingredient, it has a relatively high fiber content. The NRC (2007) reported a value of 46% of neutral detergent fiber (NDF) for SFM, which can compromise animal intake and nutrient digestibility.

Evidence shows that including SFM in the diet reflects the optimal level for each species. Including up to 45% of SFM in the diet of growing dairy cattle effectively replaced SBM (Garcia et al., 2006). However, Oliveira et al. (2018) concluded that using SFM as a replacement for SBM mixture in diet reduces nutrient use performance and efficiency in lactating dairy cows.

The understanding of how the SFM inclusion in growing lamb diets affects the animal performance, nutrient digestibility, and respirometric parameters can provide the information that contributes to determine the optimum level of this protein source in sheep diet. The overall goal of this study was to evaluate the nutritional value of sunflower meal as well as evaluate its potential to be used as a protein source in diets of growing sheep.

2. Material and Methods

The experiment was conducted in an experimental area of animal production in Montes Claros, MG, Brazil (16°43'41" S, 43°51'54" W). The research on animals was conducted according to the institutional committee on animal use (protocol 189/2015).

2.1. *In vitro* digestibility trial

Four diets with different levels of sunflower meal inclusion were formulated: 0, 100, 200, and 300 g SFM/kg of dry matter (DM) (Table 1). The diets were prepared according to the recommendations of NRC (2007) for lambs with 30 kg of body weight (BW) and a daily gain of 300 g. The diets were based on roughage (corn silage – 10.01% CP, 56.7% NDF, 5.6% mineral matter [MM], and 2.8% EE) and concentrated mixtures of SBM (50.78% CP, 9.8% NDF, 5.2% MM, and 2.4% EE), corn (9.72% CP, 4.2% NDF, 2.7% MM, and 8.80% EE), SFM and minerals (Table 1).

Table 1 - Ingredients and chemical composition of experimental diets and sunflower meal (SFM), expressed in g/kg of DM

	Ingredient composition				
	0 SFM	100 SFM	200 SFM	300 SFM	Sunflower meal
Corn silage	400.0	400.0	400.0	400.0	-
Soybean meal	264.0	196.0	118.0	18.0	-
Corn	315.0	281.0	256.0	261.6	-
Sunflower meal	0.0	100.0	200.0	300.0	-
Vitamin-mineral supplement[1]	10.5	15.0	22.0	20.4	-
Dicalcium phosphate	10.5	8.0	4.0	-	-
	Chemical composition				
Dry matter (DM, as fed)	643.4	641.7	653.3	658.8	921.9
Mineral matter	45.0	43.2	45.7	46.1	59.7
Crude protein	207.9	203.8	195.6	179.5	341.0
Neutral detergent fiber	273.4	289.9	312.9	333.1	435.3
Acid detergent fiber	176.3	212.5	227.2	302.8	306.4
Ether extract	45.2	43.2	41.8	40.5	19.2
Non-fibrous carbohydrates	428.5	413.4	404.0	400.8	144.8
Total carbohydrates	701.9	703.3	716.9	733.9	580.1
Total digestible nutrients	744.7	736.6	666.8	662.0	-

[1] Composition of mineral-vitamin premix: calcium, 150 g; phosphorus, 65 g; sodium, 130 g; fluorine, 50 mg; sulfur, 12 g; magnesium, 10 g; iron, 1000 mg; manganese, 3000 mg; cobalt, 80 mg; zinc, 5000 mg; iodine, 60 mg; selenium, 10 mg; vitamin A, 50000 IU; vitamin E, 312 IU.

Samples of experimental diets were incubated, and the pressure and volume of the gases were measured according to the methodology described by Azevedo et al. (2020), with some adaptations. The diets were incubated in bottles (160 mL), previously injected with CO_2, according to the semi-automatic *in vitro* gas production technique. Further, 1.0 g of sample was added to each bottle with 90.0 mL of culture medium for each treatment, the incubation was done at 39 °C. They were then sealed using rubber stoppers. Inoculation (10.0 mL/vial) was performed using the ruminal liquid from three rumen fistulated and grass-fed (*Brachiaria* sp.) cattle (non-lactating, 5/8 Holstein × Zebu), receiving 2 kg of concentrate containing SFM daily. The ruminal liquid was collected and transported to the laboratory.

The pressure in the bottles was measured using a pressure indicator (T443A; BAILEY, MACKEY, UK). Pressure readings were taken after 2, 4, 6, 8, 10, 12, 14, 17, 20, 24, 28, 34, 48, 72, and 96 h of incubation to calculate gas volume. We used the equation $V = -0.02 + 4.30p + 0.07p^2$, $R^2 = 0.99$, for local altitude, in which V = total gas volume and p is the gas pressure within the fermentation bottles (psi = pressure per square inch). From each pressure reading, the total gases produced in bottles without the substrate (white) for each sample were subtracted.

The bi-compartmental model proposed by Schofield et al. (1994) was used to describe the fermentation process kinetics through the cumulative production of gases in the rapid phase Vf1 (mL/g), corresponding to the fermentation of non-fibrous carbohydrates (NFC, fractions A + B1), specific degradation rate of fast fraction Kd1 (1/h), gases in the slow phase Vf2 (mL/g), corresponding to fermentation of fibrous carbohydrates (fraction B2), specific fractional slow degradation rate Kd2 (1/h), and colonization time L (h), according to the equation: V (t) = (Vf1 / (1 + exp (2-4 * Kd1 * (TL))) + (Vf2 / (1 + exp (2-4 * Kd2 * (TL))), in which V (t) is the accumulated volume at time t, Vf1 = volume of gas from the rapidly degradation fraction (NFC), Kd1 (1/h) = degradation rate of fast fraction (NFC), L = latency or colonization time in hours, T = time (h), Vf2 = volume of gas from the slow degradation fraction gas (B2), and Kd2 (1/h) = degradation rate of fraction B2.

2.2. Performance trial

Twenty-four Dorper × Santa Inês crossbred uncastrated male lambs, with an average age of 5 mo and an average initial BW of 27.91±6.0 kg, were randomly distributed among four treatments with different inclusion levels of SFM (0, 100, 200, and 300 g of SFM/kg of DM) (Table 1).

Animals were blocked into three randomized blocks according to their initial BW with mean body weights of 23.9, 25.9, and 29.1 kg in the first, second, and third blocks, respectively. The experiment lasted 66 days, of which 10 days were used for adaptation to the diets and installations (Farenzena et al., 2017), and 56 days for data and sample collection.

At day zero of experimental period, the animals were individually identified, weighed, treated for ecto- and endo-parasites (Ripercol® L – 150F, Zoetis), and immunized for clostridiosis. They were kept in individual pens (2.0 × 1.20 × 1.10 m) with access to drinking water and feeders.

Feed was provided daily at 08:00 and 16:00 h. The amount of feed offered to each lamb was recalculated daily to achieve 15–20% leftovers. Diets and leftovers were weighed daily, sampled at 35% of the total daily amount for each animal, packaged, and stored in a freezer (−20 °C) for further chemical analysis.

At the beginning and at the end of experimental period, the animals were fasted for 18 h (water was allowed *ad libitum*) and weighed. During the experimental period, the animals were weighed every seven days, and the average daily weight gain and feed conversion were calculated to determine the performance.

We evaluated the ingestive behavior according to the methodology described by Macedo Junior et al. (2019), in which the animals were subjected in a period of 24 h subdivided into three periods of 8 h in the morning, afternoon, and evening. Observations were made by four trained observers strategically positioned to avoid disturbing the animals. During the 24-h period, the time spent feeding, ruminating and idling was recorded every 5 min. Total chewing time was determined by adding the feeding and rumination times to the time spent ruminating three ruminal boluses at three different times of the day.

The feeding and rumination efficiencies for DM and NDF were determined according the methodology proposed by Bürger et al. (2000): FEDM = DMI FT^{-1}, FENDF = NDFI FT^{-1}, REDM = DMI RUM^{-1}, RENDF = NDFI RUM^{-1}, in which FEDM = feeding efficiency of dry matter, DMI = dry matter intake, FT = feeding time, FENDF = feeding efficiency of neutral detergent fiber, NDFI = neutral detergent fiber intake, REDM = rumination efficiency of dry matter, RUM = rumination time, RENDF = rumination efficiency of neutral detergent fiber.

2.3. *In vivo* digestibility trial

At the end of the performance trial, the animals were housed in individual metabolism cages and fed experimental diets for total collection digestibility trial. During a 5-d collection period, feed intake was recorded, and fecal and urine samples were collected. Representative samples of leftovers, feces, and urine were collected daily. To avoid loss of nitrogenous compounds by volatilization, 100 mL of 10% sulfuric acid (H_2SO_4) was added to the urine collectors. The samples were frozen at −20 °C for subsequent laboratory analyses.

Dry matter, CP, NFC, and NDF intakes were calculated based on the difference in the daily weight offered and leftover. The *in vivo* digestibility of each chemical component (DM, CP, NFC, and NDF) was calculated for each animal using the average individual nutrient intake and fecal output. Nutrient digestibility (ND) was obtained using the following formula: ND = [(ingested DM × nutrient concentration) – (excreted DM × nutrient concentration)] / (ingested DM × nutrient concentration).

2.4. Respirometric trial

The O_2 consumption (VO_2), CO_2 (VCO_2), and methane (VCH_4) production data were recorded using a Sable System (Sable Systems International, Las Vegas, NV, USA, according to Rodríguez et al. (2007). The animals were individually placed in a respirometry chamber for 24 h, and the same dietary treatment offered during the *in vivo* digestibility trial was supplied to each lamb once in the morning.

Ambient air flowed through the chamber at a controlled flow rate based on the animal's weight (0.6 liters/kg of body weight/minute), and it was mixed with the exhaled air. Samples were taken every 5 min for 24 h to determine O_2, CO_2, and CH_4 concentrations. All the data were recorded using an automated data acquisition program (Expedata, Sable Systems International).

The maximum allowable CO_2 concentration in the chamber is 1.0%. VO_2, VCO_2, and VCH_4 were calculated by comparing the composition and volume of air that flowed through the respirometry chamber and the air released. The temperature was maintained at 22 °C by placing an air conditioner inside the chamber to provide thermal comfort to the animals.

Heat production (HP) was estimated using the respirometry chamber technique, according to the equation of Brouwer (1965). For the transformation of data into calories, the value of 1 joule corresponding to 0.239 calories was used as a reference.

$$HP\ (kj) = 16.18 \times VO_2\ (L) + 5.02 \times VCO_2\ (L) - 5.88 \times UN\ (g) - 2.17 \times VCH_4\ (L),$$

in which HP = estimation of heat production and UN = urinary nitrogen.

The respiratory quotient (RQ) was calculated as the ratio between VCO_2 and VO_2. For calculations involving methane production, factors of 13.334 kcal/g and 0.7143 g/L were used for energy and density, respectively (Rodríguez et al., 2007).

2.5. Chemical analysis

The samples of the diets, leftovers, and feces were ground in a Willey grinder with 1 mm diameter sieves and were analyzed according to the AOAC (2005) for DM (method 934.01), ash (method 942.05), CP (method 954.01), and EE (method 920.39). Analyses of NDF and acid detergent fiber (ADF) were

performed according to Van Soest et al. (1991) using an ANKOM200 fiber analyzer unit (ANKOM Technology Corporation, Fairport, New York, USA). Heat-stable alpha amylase was used in all aliquots (Termamyl 2X, Novozymes). Non-fiber carbohydrates were calculated as follows: NFC = 100 – (% NDF + % EE + % CP + % Ash).

2.6. Statistical analysis

Data were tested for normality of residuals and homogeneity of variance. The data were analyzed using the statistical model:

$$Y_{ijk} = \mu + B_i + T_j + E_{ij},$$

in which Y_{ijk} = dependent variable; μ = general average, B_i = block effect (initial weight), T_j = effect of inclusion levels (0, 100, 200, and 300 g of SFM/kg), and E_{ij} = experimental error associated with all observations. Data were subjected to variance and regression analyses using the package SAEG (System for Statistical Analysis, version 9.1).

3. Results

Dry matter intake (DMI) and organic matter (OM) intake were not influenced by the SFM inclusion level, with averages of 1612 g of DM/day and 1487 g of OM/day**.** The DMI was 28.8% higher than that recommended by the National Research Council for growing animals, with a gain of 300 g/day. There was a quadratic response in DMI expressed in g/kg$^{0.75}$ BW (P = 0.003), according to the increase in the byproduct level (Table 2), with minimum points of 90.56 g/kg$^{0.75}$ BW for inclusion levels of 96 g of SFM/kg.

The CP intake was not influenced by the inclusion level of SFM (P = 0.1726); CP intake (404.61 g/day and 23.51 g/kg$^{0.75}$ BW) was higher than that recommended by the National Research Council (180 g/day and 9.6 g/kg$^{0.75}$ BW) for farmed sheep. In contrast, EE (P = 0.0001), and NFC (P = 0.0001) intakes decreased linearly, and NDF increased linearly after byproduct inclusion (P = 0.0001).

Despite the changes in nutrient intake, SFM inclusion in the diet did not affect the daily weight gain of the animals, with average values of 299.03 g/day (Table 2). However, the DM feed conversion showed a quadratic response (P = 0.0467) with an increase in byproduct level. The minimum points of feed conversion were 5.16 for inclusion levels of 88 g of SFM/kg.

Table 2 - Nutrient intake and weight gain of lambs fed different inclusion levels of sunflower meal

Item	Sunflower meal (g/kg of DM)				CV (%)	P-value	
	0	100	200	300		Linear	Quadratic
Intake (g/kg$^{0.75}$ BW)							
Dry matter (DM)[1]	92.60	89.93	93.34	98.63	3.50	0.0124	0.0030
Organic matter[2]	85.76	82.34	86.54	90.78	3.53	0.0184	0.0041
Crude protein	23.42	22.64	23.66	24.30	4.53	0.3495	0.1726
Ether extract[3]	5.54	4.14	3.46	3.48	3.93	0.0001	0.0001
Neutral detergent fiber[4]	17.89	23.81	33.34	42.42	3.24	0.0001	0.0001
Non-fibrous carbohydrates[5]	38.81	31.24	27.46	19.31	4.37	0.0001	0.0001
Initial body weight (kg)	29.98	27.31	27.87	26.97	3.63	0.1047	0.1311
Final body weight (kg)	46.58	46.16	44.06	41.83	5.56	0.1142	0.1431
Weight gain (g/d)	300.44	326.78	290.47	271.42	13.12	0.2897	0.1261
FC (g DM/g gain weight)[6]	5.40	4.93	5.66	6.03	10.98	0.0580	0.0467

BW - body weight; FC - feed conversion; CV - coefficient of variation.
[1] $y = 0.000199x^2 - 0.0382x + 92.39$; $R^2 = 0.9702$.
[2] $y = 0.000191x^2 - 0.03819x + 85.381$; $R^2 = 0.9139$.
[3] $y = 5.184 - 0.00688x$; $R^2 = 0.8769$.
[4] $y = 16.897 + 0.0831x$; $R^2 = 0.980$.
[5] $y = 34.54 - 0.0520x$; $R^2 = 0.690$.
[6] $y = 0.000021x^2 - 0.00368x + 5.322$; $R^2 = 0.810$.

The time spent feeding, ruminating, and idling did not differ among treatments (Table 3), with means of 202.53 min/d (P = 0.1252), 609.96 min/d (P = 0.1194), and 626.43 min/d (P = 0.7126), respectively. Similarly, the efficiency of DM feeding and DM ruminating did not differ with byproduct inclusion, with averages of 488.36 g/h (P = 0.0597) and 162.23 g/h, respectively (0.8433). Despite this, there was a difference among treatments for feed efficiency and rumination in NDF, with averages of 150.68 g/h (P = 0.0001) and 49.66 g/h (P = 0.0001), respectively. The chewing time per bolus and the total number of chews were not influenced by the byproduct inclusion, with average values of 22.45 s/bolus (P = 0.1927) and 1962.52 chews/d (P = 0.1230), respectively.

Sunflower meal inclusion linearly reduced NFC degradation, the degradation of fibrous carbohydrates, and the total degradation and increased the colonization time (L) (Table 4). With SFM inclusion, a quadratic effect on the degradation rates (Kd1) (P = 0.0018) and (Kd2) (P = 0.0002) was observed.

The digestibility of DM (P = 0.0001), NFC (P = 0.0001), and NDF (P = 0.0003) reduced linearly with SFM inclusion (Table 5); however, SFM addition had no effect (P = 0.1252) on the digestibility coefficient of CP, with an average of 795.1 g/kg.

No effect of different levels of SFM inclusion was observed on VO_2 (P = 0.207), VCH_4 (P = 0.217), and HP (P = 0.079). The mean consumption of O_2 was 25.34 L/kg$^{0.75}$ BW/d (Table 6). We observed a quadratic behavior (P = 0.019) for VCO_2 with SFM inclusion, with an estimated minimum production point

Table 3 - Ingestive behavior of lambs fed different inclusion levels of sunflower meal

Item	Sunflower meal (g/kg of DM)				CV (%)	P-value	
	0	100	200	300		Linear	Quadratic
Feeding time (min/d)	181.5	216.9	207.1	204.6	13.68	0.1825	0.1252
Rumination time (min/d)	568.7	596.2	618.2	656.7	13.03	0.3804	0.1194
Idleness time (min/d)	688.9	625.4	613.3	578.1	12.12	0.3121	0.7126
FEDM (g/h)	551.9	446.4	471.7	483.5	13.43	0.0942	0.0597
FENDF (g/h)[1]	106.7	118.7	169.3	208.0	15.60	0.0001	0.0001
REDM (g/h)	177.9	165.9	155.5	149.6	16.51	0.4187	0.8433
RENDF (g/h)[2]	34.5	44.2	55.5	64.3	15.28	0.0001	0.0001
CTRB (s/bolus)	21.0	21.9	24.1	22.7	10.34	0.2158	0.1927
TNC (n/d)	1862.3	2030.3	2106.8	1870.0	9.15	0.8126	0.1230

CV - coefficient of variation; FEDM - feeding efficiency of dry matter; FENDF - feeding efficiency of neutral detergent fiber; REDM - rumination efficiency of dry matter; RENDF - rumination efficiency of neutral detergent fiber; CTRB - chewing time per rumen bolus; TNC - total number of chewing.
[1] $y = 97.48 + 0.3547x$; $R^2 = 0.7316$.
[2] $y = 34.56 + 0.1006x$; $R^2 = 0.6742$.

Table 4 - Means and coefficient of variation (CV) of kinetic parameter estimates of *in vitro* gas production

Item	Sunflower meal (g/kg of DM)				CV (%)	P-value	
	0	100	200	300		Linear	Quadratic
Vf1 (mL/g)[1]	142.30	124.92	85.69	102.54	10.34	0.0001	0.0019
Kd1 (1/h)[2]	0.059	0.062	0.075	0.059	10.33	0.2088	0.0018
L (h)[3]	3.940	4.177	4.308	4.789	5.20	0.0001	0.1956
Vf2 (mL/g)[4]	119.58	107.96	116.18	73.63	11.32	0.0001	0.0055
Kd2 (1/h)[5]	0.025	0.026	0.029	0.023	7.39	0.366	0.0002
Total (mL/g)[6]	261.88	236.88	211.73	190.66	3.28	0.0001	0.4699

Vf1 - maximum production volume of gas for non-fibrous carbohydrate (NFC) fraction; Kd1 - degradation rate of NFC fraction; L - lag time; Vf2 - maximum production volume of gas for fibrous carbohydrate (FC) fraction; Kd2 - degradation rate of FC fraction.
[1] $y = 0.0009x^2 - 0.4152x + 146.2$; $R^2 = 0.836$.
[2] $y = -0.0000005x^2 + 0.0002x + 0.0571$; $R^2 = 0.565$.
[3] $y = 0.027x + 3.90$; $R^2 = 0.934$.
[4] $y = -0.0008x^2 + 0.1023x + 116.05$; $R^2 = 0.812$.
[5] $y = -0.0000002x^2 + 0.00005x + 0.0245$; $R^2 = 0.677$.
[6] $y = 0.239x + 261.11$; $R^2 = 0.998$.

of 149 g SFM/kg. A quadratic behavior was observed for the RQ with SFM inclusion (P = 0.025), estimating a minimum RQ of 0.92 with 139 g SFM/kg (Table 6). The RQ found in this study indicated the predominant metabolism of carbohydrates and proteins, ranging from 0.85 to 0.96.

Table 5 - Means and coefficient of variation (CV) for nutrient digestibility of lambs fed different inclusion levels of sunflower meal

Item	Sunflower meal (g/kg of DM)				CV (%)	P-value	
	0	100	200	300		Linear	Quadratic
dDM (g/kg)[1]	759.2	719.9	660.2	642.8	7.84	0.0001	0.0001
dNFC (g/kg)[2]	781.5	734.5	676.7	653.5	8.02	0.0001	0.0001
dNDF (g/kg)[3]	601.8	575.0	486.7	492.3	13.04	0.0003	0.0012
dCP (g/kg)	809.3	784.8	777.1	809.0	4.30	0.9070	0.1252

dDM - digestibility of dry matter; dNFC - digestibility of non-fibrous carbohydrates; dNDF - digestibility of neutral detergent fiber; dCP - digestibility of crude protein.
[1] $y = 756.86 - 0.4009x$; $R^2 = 0.9635$.
[2] $y = 759.63 - 0.381x$; $R^2 = 0.996$.
[3] $y = 601.47 - 0.417x$; $R^2 = 0.8553$.

Table 6 - Means and coefficient of variation (CV) for respirometric parameters in lambs fed different inclusion levels of sunflower meal

Item	Sunflower meal (g kg^{-1})				CV (%)	P-value	
	0	100	200	300		Linear	Quadratic
VO_2 (L/$kg^{0.75}$ BW)	26.10	27.03	24.31	27.52	8.15	0.702	0.207
VCO_2 (L/$kg^{0.75}$ BW)[1]	24.11	22.79	20.84	26.39	10.33	0.285	0.019
VCH_4 (L/$kg^{0.75}$ BW)	2.44	2.19	2.02	2.35	24.66	0.646	0.217
HP (kcal/$kg^{0.75}$ BW)	127.18	129.25	118.45	135.37	7.67	0.451	0.079
RQ[2]	0.928	0.896	0.846	0.960	10.31	0.505	0.025

BW - body weight; HP - heat production; RQ - respiratory quotient.
[1] $y = 0.00017x^2 - 0.0466x + 24.518$; $R^2 = 0.797$.
[2] $y = 0.000005x^2 - 0.00127x + 0.9277$; $R^2 = 0.993$.

4. Discussion

The quadratic behavior for DMI was related to SFM inclusion, which decreased the *in vivo* digestibility of DM and reduced the energy available for animals. The minimum point for DMI was observed with 96 g of SFM/kg of DM. From this level of SFM, the animals needed to increase their DMI to meet the necessary energy requirements. Some studies have reported that SFM is utilized at a less efficient rate than SBM, which results in increased feed intake of SFM compared with SBM (Nedelkov, 2019; Nedelkov et al., 2021).

The reduction in EE and NFC intake is likely due to the change in the concentration of corn and SBM with SFM inclusion, resulting in an increase in fiber content and a reduction in NFC and EE (Table 1). Concerning NDF, the linear increase in the average intake may be justified by the increase in NDF concentration in the diet with the byproduct inclusion.

The decrease of *in vivo* digestibility of DM, NFC, and NDF with SFM inclusion can be associated with the reduction in non-fibrous carbohydrates in the diets. The reduction in NFC affects the synchronicity between NFC and CP and the development of the ruminal microbiota (Zhang et al., 2020). Non-fibrous carbohydrates are fermented quickly, consequently providing greater energy input for microbial growth and resulting in greater carbohydrate digestibility. Similar results were found by Leira et al. (2010) in digestibility studies with goats receiving isonitrogenous diets with different proportions of SFM and corn. They observed that NDF digestibility decreases with an increase in SFM inclusion and a reduction in corn participation in the diet.

The linear reduction in total degradation with SFM inclusion and the increase in colonization time are probably due to the fiber quality of the byproduct and reduction in the NFC fraction in the diets with increasing SFM levels. Mendes et al. (2006) suggested that the use of sunflower meal, associated with readily available energy sources, can maximize ruminal digestion. According to Nedelkov (2019), the average value of the effective DM degradability of SFM at the mean rumen outflow rate was lower than that of the SBM samples. One potential explanation is the higher fiber content of SFM, which, compared with other nutrients, degrades slowly in the rumen.

The weight gain average of the animals was 299.0 g/day. Stoycheva (2021) found no significant differences in the weight gain of female lambs, weighing 19.4 kg, for reproduction when fed SFM instead of SBM plus peas. According to the author, this indicates that the acceptability of SFM is good.

Feed conversion is an important parameter in the economic evaluation of diets. The minimum points of feed conversion were 5.16, for inclusion levels of 87.8 g of SFM/kg, which is higher than the 4.0 recommended by the NRC (2007) for animals at this developmental stage. The results obtained in this study demonstrate that, above the inclusion level of 87.8 g of SFM/kg, animals need to consume larger amounts to convert the feed into 1 kg of BW, which, in practice, may increase production cost, depending on the substitute price, the product, and the byproduct.

The high NDF content of SFM, classified as a fibrous byproduct, would increase the time spent by animals on rumination due to the higher chewing need for fiber breakage, thereby reducing idle time. The absence of this behavior, however, may be justified by lamb selectivity and the low effectiveness of the fibrous fraction of the byproducts because its physical processing (grinding) resulted in particles with sizes similar to those of the substituted concentrates, such as corn and SBM. According to Costa et al. (2021), lambs fed diets with high concentrate levels can adjust their selectivity to compensate for low dietary fiber concentrations.

Despite this, a difference was observed among treatments for feed efficiency and rumination efficiency in NDF. This is likely due to the higher fiber intake with SFM inclusion in the diet; in fact, the feed efficiency and the rumination efficiency in NDF increased proportionally with increasing SFM levels in the diet. Cardoso et al. (2006) working with crossbred Ile de France × Texel lambs, also reported a linear increase in the feeding efficiency and NDF rumination as a result of an increase in dietary fiber levels. They also concluded that knowledge of ingestive behavior is important for adjusting feed management to maximize productive performance.

There was no variation in VO_2, VCH_4, or urinary nitrogen excretion among treatments. These factors were reflected in the similar HP of the animals, despite the difference in VCO_2. According to Wang et al. (2021), energy use is positively related to CH_4 emissions. The levels of NDF in the diets ranged from 273.4 to 333.1 g/kg DM. However, this variation was not enough to change methane production. Therefore, the energy metabolism of the animals also showed no change. Rossi et al. (2001) showed that the *in vitro* CH_4 production (mM/g of dry matter) after 24 h post-incubation in the rumen after SFM diet was lower than that after SBM diet and concluded that SFM is energetically effective and environmentally cleaner than SBM as ruminant feed.

The average HP value was 122.9 kcal/kg$^{0.75}$ BW/day, which is similar to that reported by NRC (2007) with 131.84 kcal/kg$^{0.75}$ BW/day of net energy for growing lambs. The similarity found for the VO_2, VCH_4, and HP of the animals indicates that the lower availability of nutrients with SFM inclusion was not sufficient to change the energy metabolism of the animals.

5. Conclusions

The inclusion of up to 300 g of SFM/kg in diets of growing lambs reduced the nutritional value of the diets. Our findings suggest a maximum inclusion point of 88 g SFM/kg when considering the feed conversion rate, which is a necessary factor in evaluating the replacement cost.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Conceptualization: L.C. Geraseev. Data curation: L.C. Geraseev, N.C. Silva, A.S. Chaves, D.S. Costa, L.T.C. Ornelas and L.F. Crocomo. Formal analysis: L.C. Geraseev and A.S. Chaves. Funding acquisition: L.C. Geraseev. Investigation: L.C. Geraseev, N.C. Silva, A.S. Chaves, D.S. Costa, L.T.C. Ornelas, L.F. Crocomo and S.J.M. Moreira. Project administration: L.C. Geraseev and A.S. Chaves. Resources: L.C. Geraseev. Supervision: L.C. Geraseev and A.S. Chaves. Validation: L.C. Geraseev and A.S. Chaves. Visualization: N.C. Silva, D.S. Costa, L.T.C. Ornelas and S.J.M. Moreira. Writing – original draft: L.C. Geraseev, N.C. Silva, A.S. Chaves, D.S. Costa, L.T.C. Ornelas, L.F. Crocomo and S.J.M. Moreira. Writing – review & editing: L.C. Geraseev, N.C. Silva and A.S. Chaves.

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