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Original

Productivity and carcass characteristics obtained in calcium propionate-supplemented sheep

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ABSTRACT

Objective. Evaluate the effect of the inclusion of calcium propionate (CaP) on productive variables and carcass characteristics in finishing lambs. **Materials and methods.** 24 male lambs of the Dorper x Pelibuey cross of 5 months of age were used, with an average body weight (μ ± SD) of 27±2.7 kg. Were assigned to one of three treatments (control [CON] and two CaP levels: 10 and 20 g/kg DM) in a completely randomized design (3 treatments, 8 repetitions per treatment, considering each lamb as an experimental unit). Response variables were reduced to 1 mean value for each lamb, and data were analyzed in SAS version 9.4 using Proc Mixed. **Results.** Daily weight gain (DWG), conversion (FCE) and feed efficiency (FEU) were higher by 13, 20 and 24%, respectively, due to the inclusion of 20 g CaP/kg DM (p≤0.05). Chilled carcass weight (CCW), hot carcass dressing (HCD) and cold carcass dressing (CCD) were higher when increasing the inclusion level of CaP (p≤0.05). **Conclusions.** Supplementation with CaP in doses of up to 20g / kg in finishing diets can improve production parameters and carcass performance without affecting dry matter intake (DMI).

Keywords: Lambs; propionate; yield (*Source: USDA*).

RESUMEN

Objetivo. Evaluar el efecto de la inclusión de propionato de calcio (PCa) sobre variables productivas y características de la canal en corderos en finalización. **Materiales y métodos.** Se utilizaron 24 coderos machos de la cruza Dorper x Pelibuey de 5 meses de edad, con un peso corporal promedio (μ±SD) de 27±2.7 kg. Fueron asignados a uno de tres tratamientos (control [CON] y dos niveles de PCa: 10 y 20 g/kg de MS) en un diseño completamente al azar (3 tratamientos, 8 repeticiones por tratamiento, considerando cada cordero como una unidad experimental). Las variables de respuesta se redujeron a 1 valor medio para cada cordero, y los datos se analizaron en SAS versión 9.4 usando

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Proc Mixed. **Resultados.** La ganancia diaria de peso (GDP), conversión (CA) y eficiencia alimenticia (EF) fueron mayores en 13, 20 y 24%, respectivamente por la inclusión de 20 g de PCa/kg MS ($p \leq 0.05$). El peso de la canal fría (PCF), rendimiento en canal caliente (RCC) y rendimiento en canal fría (RCF) fueron mayores al incrementar el nivel de inclusión de PCa ($p \leq 0.05$). **Conclusiones.** La suplementación con PCa en dosis de hasta 20g/kg en dietas de finalización puede mejorar los parámetros productivos y de rendimiento en canal sin afectar el consumo de materia seca (CMS).

Palabras clave: Corderos; propionato; rendimiento (*Fuente: USDA*).

INTRODUCTION

Calcium propionate (CaP) is an organic salt formed from the reaction between calcium hydroxide and propionic acid (PA) (1). It is widely used as an antifungal additive to preserve the quality of high moisture feed during storage (2). Ruminants hydrolyze CaP into Ca^{2+} and PA in the rumen (1). Propionic acid is absorbed through ruminal epithelium and functions as a primary precursor for glucose hepatic synthesis (3) and may provide about 95% of this sugar (4). Glucose is a critical energy-producing nutrient (5), providing almost 80% of the metabolizable energy consumed by animals.

Calcium propionate supplementation in livestock production depends on the species, age, and physiological state. For example, in cattle, it is supplied in a 50 to 300 g/d range (6,7,8), and in growing sheep from 10 to 30 g/kg DM (9,10). The gluconeogenic potential of CaP counteracts the effects of the negative energy balance and ketosis that occurs at the beginning of lactation in dairy cows (11) when the energetic requirements for milk synthesis are not satisfied through the diet (12). It has also been used to enhance body weight gain in calves and to promote the development of their internal organs and gastrointestinal tract (13). Lee-Rangel et al (14) indicate that CaP can partially replace the energy supplied by grains in diets for finishing lambs.

Therefore, increasing the PA concentration from an exogenous CaP intake can reduce ruminal pH, improve DM, organic matter (OM), neutral detergent fiber (NDF), and acid (ADF) digestibility, and increase nutrients and energy availability (8); improving the daily weight gain (DWG), feed conversion (FCE), yield and composition of the carcass. It can also act as a metabolic mediator with a hypophagic effect on the animals due to its capacity to stimulate the oxidation of hepatic acetyl CoA (15). Nevertheless, the results for dry matter intake (DMI) have been inconsistent and are attributed to the animal's nutritional level, the nutritional value of the diet, the level of CaP incorporation, and the purity level of the product (6,16,17). The assessed hypothesis is that supplemented CaP in diets for growing lambs improves the production parameters, without affecting the DMI. The objective of this research is to determine the productive response and carcass characteristics of lambs supplemented with a propionic acid calcium salt.

MATERIALS AND METHODS

Ethical aspects. All procedures performed on the assessed animals strictly followed the Mexica Official Norm (NOM-062-ZOO 1999). The experimental period began once the protocol for the usage and handling of animals was approved.

Experimental area. Research was conducted at the experimental farm of the Colegio de Postgraduados, Campus Montecillo, in the ruminant nutrition area (19°27’35’’ N, 98°54’24’’ W and 2244 m altitude) in Texcoco, Mexico. The climate, according to the Köppen classification, is Cw (temperate sub-humid) with rainy seasons (spring-summer). The annual average temperature and precipitation in the area are 15°C and 500 mm, respectively.

Experimental design and diets. Twenty-four lambs (Dorper x Pelibuey), 21 weeks of age and 27±2.7 kg body weight ($\mu \pm SD$) were assessed in a completely randomized design and assigned to one of three treatments (control [CON] and two CaP levels: 10 and 20 g/kg DM) with eight replicates each (considering each lamb as an experimental unit). The experimental diets (Table 1) consisted of a totally mixed ration (TMR) in a 60% forage and 40% concentrate ratio, covering the nutritional requirements for growing and finishing lambs (18). The diets were formulated to provide a similar level of energy and protein. A percentage of ground corn was replaced with the same amount of CaP

(10 and 20 g/kg) in the TMR to establish the experimental treatments.

The CaP was completely mixed, according to the proposed proportions, with 1 kg of ground corn (vehicle), then with the remaining concentrate, and finally with forage over a 25 min period in an AZTECA® horizontal ribbon mixer. The lambs were fed in two services (8:00 and 15:00 h), offering 70% of the diet in the morning and the remaining 30 % in the afternoon. A daily 10% feed surplus was provided.

Table 1. Ingredients proportion in the rations.

Ingredients (g/kg DM)	CaP incorporation level (g/kg DM)		
	CON	**10**	**20**
Corn stover	300	300	300
Alfalfa hay	300	300	300
Ground corn	270	260	250
Soybean meal	70	70	70
Cane molasses	50	50	50
Minerals[1]	10	10	10
Calcium propionate[2]	-	10	20

[1] Vitasal Engorda Ovino Plus® each kg contains: 0.5% S, 24% Ca, 12% Cl, 3% P, 2% Mg, 0.5% K, 8% Na, 5000 mg Zn, 60 mg Co, 5 mg Cr, 2000 mg Fe, 4000 mg Mn, 30 mg Se, 100 mg I, 500,000 UI vitamin A, 150,000 UI vitamin D, 1,000 UI vitamin E, 2000 mg Lasolacide and 0.05% antioxidant.
[2] Propical® Acid propionic calcium salt 94% purity.

Animal management. For their comfort, lambs were individually placed in 2 x 2 m² pens with feeders and drinkers. The entire infrastructure was in an enclosed building with concrete floors. Lambs were previously treated with ADE vitamin (2 mL per lamb; 1 mL=vitamin A: 500 thousand IU; vitamin D3: 75 thousand IU; vitamin E1: 50 mg) and ivermectin (0.5 mL per animal; 1 mL=10 mg ivermectin) intramuscularly. Water was provided *ad libitum* to all lambs. Lambs were fed with the CON diet for 15 days, before starting the experiment, for adaptation and to obtain the DMI baseline values. At the beginning of the trial, the DMI (μ ± SD) was 1.10±0.13 kg/d. Lambs were weighed using an electronic scale (TORREY TIL/S: 107 2691, TORREY electronics Inc., Houston, TX, USA) after a 14-h solids fast at 2-week intervals to determine their DWG.

Response variables. DMI (offered feed - refused feed), DWG (final weight - initial weight/42), total gain (TG; final weight - initial weight), FC (ratio between total feed consumed/TG), FEU (DWG/DMI average), final live weight (FLW), live weight at slaughter (LWS) were evaluated. After a 24-h fasting period in a commercial slaughterhouse, the slaughter was conducted following NOM-033-SAG/ZOO-2014. Then, the hot carcass weight (HCW) was immediately recorded. The carcasses were refrigerated at 4°C; after 24 h, the cold carcass weight (CCW) was then recorded. The hot (HCY) and cold (CCY) carcasses yield was obtained by: HCY = ((HCW/LWS) x 100) and CCY= ((CCW/LWS) x 100). Back-fat thickness (BTh) and chop area (ChA) were determined by ultrasonography at the beginning and end of the experimental period.

Data collection and chemical analysis. Representative diet samples per treatment were collected daily, their partial DM content was determined using a forced-air oven at 60°C for 72 h; consequently, TMR was adjusted every third day when necessary. Each sample was placed in a plastic bag and stored in a moisture-free area to avoid fungal contamination. At the end of the experimental period, individual samples were mixed for each treatment and a 15% aliquot was taken for its chemical analysis (Table 2).

Table 2. Nutrient content of the experimental diets.

Chemical composition (g/kg DM)	LCP			SE	Contrast	
	CON	**10**	**20**		**L**	**Q**
Dry Matter	904	906	901	2.38	0.41	0.28
Crude Protein	118	112	111	2.69	0.10	0.51
Neutral Detergent Fiber	711	709	718	10.07	0.64	0.63
Acid Detergent Fiber	527	535	536	4.12	0.20	0.48
Ether Extract	15	13	13	0.84	0.21	0.30
Crude Ash	87	92	99	0.43	0.01	0.07

LCP= CPr incorporation level (g/kg DM) SE = Standard error. L = Linear contrast; Q = Quadratic contrast.

Feed samples were ground through a 2 mm sieve in a Thomas Wiley® mill (Thomas-Scientific; Philadelphia, PA) and analyzed by triplicate to determine absolute DM (by drying at 100°C for 24 h). Crude ashes at 600°C for 2 h to calculate MO (method 942.05) (19), total nitrogen *via* the combustion method (LECO® CN-2000 series 3740, LECO® Instruments Inc., St. Joseph, MI, USA), ethereal extract by the acid hydrolysis method using petroleum ether as solvent (EE; method 922.06) (19). NDF and ADF contents were determined following Van Soest et al (20) using sodium sulfite, without thermostable amylase.

Statistical analysis. All response variables were reduced to one mean value for each lamb, the data were analyzed in the SAS statistical software (21) using the PROC MIXED procedure. The model used was as follows:

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

where:
Y_{ijk} = dependent variable; μ = mean; T_i = fixed treatment effect (i= 1…, 3); E_{ij} = random error assuming $E_{ij} \sim N(0, \delta^2)$.

Means were compared with the Tukey test and considered statistically significant at a p<0.05. The response trend to treatment was also analyzed by contrasts (linear and quadratic) using the PROC MIXED procedure (SAS) (21).

RESULTS

Nutrient concentrations were similar among treatments (p>0.05) (Table 2). FLW, DMI, TG, ChA, and BTh were not modified by the CaP supplement (p>0.05) (Table 3). DWG and FEU linearly increased (p≤0.05) (Table 3), improving by 13 and 24 % respectively, by incorporating 20 g of CaP. An improved FEU reciprocally improved FCE, linearly reducing (p≤0.01) (Table 3) the required feed intake to produce 1 kg of meat by 11 and 20% when the CaP level was 10 and 20 g/kg, respectively. Suppling CaP did not modify the LWS or HCW (p>0.05) (Table 4). FLW (p≤0.04), HCW, and CCY linearly increased (p≤0.01) (Table 4) as the CaP concentration in the diet increased.

Table 3. Calcium propionate effect on consumption and productive variables in Dorper*Pelibuey lambs.

Item	LCP			SE	Contrast	
	CON	10	20		L	Q
Initial live weight ($kg^{0.75}$)	11.6	12.2	11.7	0.97	-	-
Final live weight ($kg^{0.75}$)	15.0	15.7	15.5	1.18	0.32	0.30
DMI (kg d^{-1})	1.42	1.34	1.31	0.06	0.19	0.72
Total gain (kg)	10.6	11.3	12.1	0.50	0.06	0.89
Daily weight gain (g d^{-1})	253	268	287	11.8	0.05	0.87
Feed conversion (kg/DM)	5.7	5.1	4.60	0.26	0.01	0.86
Feed efficiency (g/DM)	179	211	222	9.12	0.01	0.92
Chop area (mm^2)	825	832	874	40.4	0.40	0.74
Back fat thickness (mm)	3.0	2.8	3.1	0.16	0.59	0.13

LCP= CPr incorporation level (g/kg DM); DMI=Dry matter intake; SE=Standard error; L=Linear contrast; Q=Quadratic contrast.

Table 4. Characteristics of lamb carcasses fed with increased levels of calcium propionate.

Item	LCP			SE	Contrast	
	CON	10	20		L	Q
Live weight at slaughter (kg)	35.4	37.5	36.8	1.23	0.43	0.35
Hot carcass weight (kg)	19.1	21.0	21.1	0.72	0.06	0.30
Cold carcass weight (kg)	18.5	20.3	20.7	0.71	0.04	0.44
Hot carcasses yield (%)	53.8	56.1	57.4	0.50	<0.01	0.40
Cold carcasses yield (%)	52.3	54.3	56.2	0.49	<0.01	0.89

LCP=CPr incorporation level (g/kg DM); SE=Standard error, L=Linear contrast, Q=Quadratic contrast.

DISCUSSION

Propionic acid is a final product of the ruminal fermentation of carbohydrates that enters the bloodstream, serves as an energy source and as a substrate for anabolic functions in ruminants, can act as a metabolic mediator, and can suppress DMI (22). Reductions in DMI may result from increased PA production as a dietary response to exogenous propionate supplements. PA is an anaplerotic metabolite and its hypophagic effects are probably due to its ability to stimulate hepatic acetyl-CoA oxidation (15). Increased acetyl-CoA oxidation contributes to animal satiety (23). Previous reports hypothesize that the threshold for a hypophagic effect is about 12 moles/animal/day (24). In dairy cattle, it is reported that abomasal infusions of a sodium propionate solution equivalent to 1.68 mol/day did not alter DMI (16). Supplementation of 0.22 and 0.43 mol/day of CaP in rations given to Jersey calves did not decrease DMI (8).

In contrast, Bradford and Allen (25) reported a decrease in the ingestion due to sodium propionate ruminal infusions at a 19 mol/day rate in lactating cows. The estimated molar proportions were 0.067 and 0.132 mol/day for the two CaP levels in the present study, both proportions below the threshold range for producing bottleneck hepatic effects that could alter the PA metabolism and affect the DMI (26). These results concur with others in crossbred sheep (Hampshire × Suffolk) in which no CaP effect on the DMI was reported when supplied in the 0.064 to 0.207 mol/day range (9,14,24). Researchers reports that the inconsistent results on the DMI obtained by supplying CaP are due to each animal´s physiological and nutritional status effects, the forage:concentrate ratio in the diet, the level of CaP supplementation (6,17), and the purity of the used products.

Results for FLW, TG, ChA and BTh variables reported here concur with those from previous research (9,14,24). However, Martinez-Aispuro et al (9) reported DWG increases by 17.2 and 13.8 % by supplying CaP at 10 and 20 g/kg DM; similarly, feed requirements to form one kg of live weight were lower by 14.6 and 11.9 % with these concentrations; the results are consistent with those reported here, in which FEU was also favored. Higher FEU has been reported after including gluconeogenic precursors (5).

Zhang et al (8) reported DWG higher than 300 g/day in calves supplemented with CaP 0.43 mol/day. Other research found no differences supplementing CaP in sheep rations regarding their DWG and FCE (10,14,24). An improved DWG, FCE, and FEU may be because CaP supplements can enhance nutrient use (27) and provide additional and easily available energy through increased hepatic glucose synthesis (3,6,11,17). In this research, the estimated metabolizable energy (ME) for CaP was 4.463 MCal/kg, a higher value than that reported by Mendoza-Martínez et al (24) of 3.766 MCal/kg. The rations here assessed increased metabolizable energy (ME) by an average of 1% when 10 and 20 g/kg of CaP were included. In this regard, Mendoza-Martínez et al (24) and Berthelot et al (28) reported increases of 2.5 and 10 % of ME in rations supplied with 50 g/kg of sodium propionate and 20 g/kg of CaP, respectively.

An increase in energy concentration can lead to increases in live weight. Based on the DWG, DMI and net energy (NE) requirements were predicted. The estimated NE gain coefficient for the rations with 10 and 20 g CaP/kg DM was 1.12 and 1.05, respectively; >1 values indicate efficient use of the theoretically contained NE in the diet (29). The estimated DMI coefficient was 1.03<0.90<0.85 for the CON, 10, and 20 g CaP diets, respectively; <1 values indicate increase efficiency in the NE retention per kg DM, equivalent to lower feed intake to form one kg of live weight (29). The relation between observed *vs*. estimated intake allows calculating the degree of efficiency in the energy use in the treatments (30), which was better used by lambs when CaP was included, which favored DWG, FCE, and FEU.

It has been shown that energy density influences yield and carcass composition (31). These results are alike other research in which no differences in HCW were recorded among lambs supplemented with 10 and 20 g of CaP (14,24). A linear increase in CCW could be an indirect effect of CaP supplementation since exogenous propionate promoted DWG (Table 3) and increased FLW by an average of 2 kg, in sheep receiving 10 and 20 g of CaP, therefore, muscle fat deposition could also be promoted. Animal muscle is known to be composed of, on average, 75% water (32). After slaughter, the water content decreases by evaporation, as a consequence of tissue cutting. A higher intramuscular fat content in the carcass was derived from greater glucose availability for lipogenesis (33) and reduced dehydration losses in the CaP treatments compared to the CON treatment.

Other reports on HCY and CCY are, like those presented here (33), with a linear decrease in these variables when the concentration of crude glycerin in the diets increased. The improvement in HCY and CCY when CaP is supplied in the lambs’ diet may be related to the characteristics of the diet and exogenous PA supply. For instance, other researchers report that using concentrates or glucose precursors in finishing lambs favors the PA production in the rumen and increases the carcass yield (34), compared with lambs fed with forages which show acetic-type fermentations.

In conclusion, the results reported here indicate that the supplementation of 20 g/kg CaP in the diet of finishing lambs improves DWG, FCE, and FEU, without affecting DMI. CaP can improve productivity in lambs because it enhances energy availability and improves nutrient intake from the diet; it can also significantly increase carcass yield.

Conflict of interest

The authors have no conflicts of interest to report.

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REFERENCES

1. Zhang F, Nan X, Wang H, Guo Y, Xiong B. Research on the Applications of Calcium Propionate in Dairy Cows: A Review. Animals. 2020; 10(8):1336. https://doi.org/10.3390/ani10081336

2. Dong Y, Bae HD, McAllister TA, Mathison GW, Cheng K-J. Lipid-induced depression of methane production and digestibility in the artificial rumen system (RUSITEC). Can J Anim Sci. 1997; 77(2):269-278. https://doi.org/10.4141/A96-078

3. Kennedy KM, Donkin SS, Allen MS. Effect of uncouplers of oxidative phosphorylation on metabolism of propionate in liver explants from dairy cows. J Dairy Sci. 2021; 104(3):3018-3031. https://doi.org/10.3168/jds.2020-19536

4. Larsen M, Kristensen NB. Precursors for liver gluconeogenesis in periparturient dairy cows. Animal. 2013; 7(10):1640-1650. https://doi.org/10.1017/S1751731113001171

5. Loncke C, Nozière P, Vernet J, Lapierre H, Bahloul L, Al-Jammas M, et al. Net hepatic release of glucose from precursor supply in ruminants: a meta-analysis. Animal. 2020; 14(7):1422-1437. https://doi.org/10.1017/S1751731119003410

6. Liu Q, Wang C, Guo G, Yang WZ, Dong KH, Huang YX, et al. Effects of calcium propionate on rumen fermentation, urinary excretion of purine derivatives and feed digestibility in steers. J Agric Sci. 2009; 147(2):201-209. https://doi.org/10.1017/S0021859609008429

7. Liu Q, Wang C, Yang WZ, Guo G, Yang XM, He DC, et al. Effects of calcium propionate supplementation on lactation performance, energy balance and blood metabolites in early lactation dairy cows. J Anim Physiol Anim Nutr. 2010; 94(5):605-614. https://doi.org/10.1111/j.1439-0396.2009.00945.x

8. Zhang X, Wu X, Chen W, Zhang Y, Jiang Y, Meng Q, et al. Growth performance and development of internal organ, and gastrointestinal tract of calf supplementation with calcium propionate at various stages of growth period. PloS One. 2017; 12(7):e0179940. https://doi.org/10.1371/journal.pone.0179940

9. Martínez-Aispuro JA, Sánchez-Torres MT, Mendoza-Martínez GD, Mora JLC, Figueroa-Velasco JL, Ayala-Monter MA, et al. Addition of calcium propionate to finishing lamb diets. Vet México. 2018; 5(4):1-9. https://doi.org/10.22201/fmvz.24486760e.2018.4.470

10. Cifuentes-Lopez O, Lee-Rangel HA, Mendoza GD, Delgado-Sanchez P, Guerrero-Gonzalez L, Chay-Canul A, et al. Effects of Dietary Calcium Propionate Supplementation on Hypothalamic Neuropeptide Messenger RNA Expression and Growth Performance in Finishing Rambouillet Lambs. Life. 2021; 11(6):566. https://doi.org/10.3390/life11060566

11. Orellana Rivas RM, Gutierrez-Oviedo FA, Komori GH, Beihling VV, Marins TN, Azzone J, et al. Effect of supplementation of a mixture of gluconeogenic precursors during the transition period on performance, blood metabolites and insulin concentrations and hepatic gene expression of dairy cows. Anim Feed Sci Technol. 2021; 272:114791. https://doi.org/10.1016/j.anifeedsci.2020.114791

12. Churakov M, Karlsson J, Edvardsson Rasmussen A, Holtenius K. Milk fatty acids as indicators of negative energy balance of dairy cows in early lactation. Animal. 2021; 15(7):100253. https://doi.org/10.1016/j.animal.2021.100253

13. Cao N, Wu H, Zhang XZ, Meng QX, Zhou ZM. Calcium propionate supplementation alters the ruminal bacterial and archaeal communities in pre- and postweaning calves. J Dairy Sci. 2020; 103(4):3204-3218. https://doi.org/10.3168/jds.2019-16964

14. Lee-Rangel HA, Mendoza GD, González SS. Effect of calcium propionate and sorghum level on lamb performance. Anim Feed Sci Technol. 2012; 177(3-4):237-241. https://doi.org/10.1016/j.anifeedsci.2012.08.012

15. Maldini G, Kennedy KM, Allen MS. Temporal effects of ruminal infusion of propionic acid on hepatic metabolism in cows in the postpartum period. J Dairy Sci. 2019; 102(11):9781-9790. https://doi.org/10.3168/jds.2019-16437

16. Zhang XZ, Meng QX, Lu L, Cui ZL, Ren LP. The effect of calcium propionate supplementation on performance, meat quality, and mRNA expression of finishing steers fed a high-concentrate diet. J Anim Feed Sci. 2015; 24(2):100-106. https://doi.org/10.22358/jafs/65634/2015

17. Zhang Q, Koser SL, Bequette BJ, Donkin SS. Effect of propionate on mRNA expression of key genes for gluconeogenesis in liver of dairy cattle. J Dairy Sci. 2015; 98(12):8698-8709. https://doi.org/10.3168/jds.2015-9590

18. National Research Council. Nutrient Requirements of Small Ruminants: Sheep, Goats, Cervids, and New World Camelids. Washington, DC: The National Academies Press, 2007. https://doi.org/10.17226/11654

19. AOAC International. Official Methods of Analysis: 20th ed. Rockville, Maryland, USA, 2016: AOAC International; 2016.

20. Van Soest PJ, Robertson JB, Lewis BA. Methods for Dietary Fiber, Neutral Detergent Fiber, and Nonstarch Polysaccharides in Relation to Animal Nutrition. J Dairy Sci. 1991; 74(10):3583-3597. https://doi.org/10.3168/jds.S0022-0302(91)78551-2

21. SAS. User´s guide Statistics. Version 9.0 Cary: SAS Institute Inc., 2002.

22. Radojičić B, Joksimović-Todorović M, Bukvić M, Simeunović P, Kakishev M, Pračić N. The influence of sodium propionate on blood glucose, insulin and cortisol concentrations in calves of different ages. Acta Vet Brno. 2016; 85(2):127-132. https://doi.org/10.2754/avb201685020127

23. Gualdrón-Duarte LB, Allen MS. Fuels derived from starch digestion have different effects on energy intake and metabolic responses of cows in the postpartum period. J Dairy Sci. 2018; 101(6):5082-5091. https://doi.org/10.3168/jds.2017-13607

24. Mendoza-Martínez GD, Pinos-Rodríguez JM, Lee-Rangel HA, Hernández-García PA, Rojo-Rubio R, Relling A. Effects of dietary calcium propionate on growth performance and carcass characteristics of finishing lambs. Anim Prod Sci. 2016; 56(7):1194-1198. https://doi.org/10.1071/AN14824

25. Bradford BJ, Allen MS. Phlorizin administration does not attenuate hypophagia induced by intraruminal propionate infusion in lactating dairy cattle. J Nutr. 2007; 137(2):326-330. https://doi.org/10.1093/jn/137.2.326

26. Kennedy KM, Allen MS. Hepatic metabolism of propionate relative to meals for cows in the postpartum period. J Dairy Sci. 2019; 102(9):7997-8010. https://doi.org/10.3168/jds.2018-15907

27. King TM, Beard JK, Norman MM, Wilson HC, Macdonald JM, Mulliniks JT. Effect of supplemental rumen undegradable protein and glucogenic precursors on digestibility and energy metabolism in sheep. Transl Anim Sci. 2019; 3(1):1714-1718. https://doi.org/10.1093/tas/txz064

28. Berthelot V, Bas P, Schmidely P, Duvaux-Ponter C. Effect of dietary propionate on intake patterns and fatty acid composition of adipose tissues in lambs. Small Rumin Res. 2001; 40(1):29-39. https://doi.org/10.1016/S0921-4488(00)00217-0

29. Cannas A, Tedeschi LO, Atzori AS, Lunesu MF. How can nutrition models increase the production efficiency of sheep and goat operations? Anim Front. 2019; 9(2):33-44. https://doi.org/10.1093/af/vfz005

30. Zinn RA, Barreras A, Owens FN, Plascencia A. Performance by feedlot steers and heifers: daily gain, mature body weight, dry matter intake, and dietary energetics. J Anim Sci. 2008; 86(10):2680-2689. https://doi.org/10.2527/jas.2007-0561

31. Wang Y, Wang Q, Dai C, Li J, Huang P, Li Y, et al. Effects of dietary energy on growth performance, carcass characteristics, serum biochemical index, and meat quality of female Hu lambs. Anim Nutr. 2020; 6(4):499-506. https://doi.org/10.1016/j.aninu.2020.05.008

32. Junkuszew A, Nazar P, Milerski M, Margetin M, Brodzki P, Bazewicz K. Chemical composition and fatty acid content in lamb and adult sheep meat. Arch Anim Breed. 2020; 63(2):261-268. https://doi.org/10.5194/aab-63-261-2020

33. Carvalho VB, Leite RF, Almeida MTC, Paschoaloto JR, Carvalho EB, Lanna DPD, et al. Carcass characteristics and meat quality of lambs fed high concentrations of crude glycerin in low-starch diets. Meat Sci. 2015; 110:285-292. https://doi.org/10.1016/j.meatsci.2015.08.001

34. Brant LMS, de Freitas Júnior JE, Pereira FM, Pina D dos S, Santos SA, Leite LC, et al. Effects of alternative energy and protein sources on performance, carcass characteristics, and meat quality of feedlot lambs. Livest Sci. 2021; 251:104611. https://doi.org/10.1016/j.livsci.2021.104611