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Effect of Dietary Calcium Propionate Inclusion Period on the Growth Performance, Carcass Characteristics, and Meat Quality of Feedlot Ram Lambs

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Abstract: The objective was to determine the effect of calcium propionate (CaPr) inclusion in the diet, at different periods on the growth performance, carcass characteristics, and meat quality of finishing lambs. Thirty-six Dorper × Katahdin crossbred male lambs (39.1 ± 0.44 kg BW) were housed in individual pens during a 42 d feeding period and assigned to four treatments (n = 9) consisting of CaPr administered at a dose of 10 g/lamb/d for 0 (control), 14, 28, or 42 d before slaughter. Final BW (FBW), average daily gain (ADG), dry matter intake (DMI), and ADG:DMI ratio increased quadratically ($p < 0.05$) by CaPr supplementation, being optimal at an estimated inclusion period of 25 d for FBW and ADG, 15 d for DMI, and 28 d for ADG:DMI ratio. Hot carcass weight (HCW), cold carcass weight (CCW), and dressing were quadratically improved ($p < 0.05$) at an estimated inclusion period of 24 d for HCW and CCW, and 20 d for dressing. The increased inclusion period (42 d) augmented fat thickness (linear effect, $p < 0.05$). At 28 d of CaPr supplementation, maximal response (quadratic effect, $p < 0.05$) was estimated in the empty body weight at 28 d, forequarter at 26 d, and neck at 24 d, but a longer inclusion period (42 d) increases the weight of leg and rack and reduced the proportion of loin as a percentage of CCW (linear effect, $p < 0.05$). In conclusion, dietary CaPr can be included for a period of 24 to 28 d to improve growth performance and carcass weight, without affecting organ mass or meat quality.

Keywords: crossbred lambs; gluconeogenic precursor's; dietary energy; feedlot

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1. Introduction

Feedlot finishing of lambs is more frequent nowadays. These feeding systems require high energy density provided diets mainly by large amounts of cereal grains [1–3]. However, cereals are expensive, and when included in high dietary levels (greater than 60%), they precipitate ruminal acidosis [4–6] leads to liver abscesses, which are related to reductions of 6% dry matter intake (DMI) and 25% the average daily gain (ADG) [7], and the increase in the morbidity rate and/or the severity of morbidity (days in medical treatment) [8].

As a result, research on alternative non-conventional energy sources that pose a lower risk of acidosis, such as gluconeogenic precursors [9,10] like calcium propionate (CaPr) [11], glycerol [12], propylene glycol [13], and sodium propionate [14], is gaining popularity. The energy contribution of CaPr is similar to that of propionic acid [15], and promising results have been reported [9,10]. In addition, it is approved by the World Health Organization (WHO) and the United Nations Food and Agriculture Organization (FAO) for use in food or feed additives [16].

Previous reports have consistently shown that increasing dietary energy improves the growth performance of finishing lambs [2,17–19]. It has been found that CaPr dissociates in the rumen, releasing calcium ions and propionate, leading to an enhanced energy status through increased glucose synthesis in the liver [20].

In finishing lambs supplemented with CaPr for 42 d, Carrillo-Muro et al. [11] found that the dose of 10 g of CaPr per lamb per day increased DMI by 13%, ADG by 28%, ADG:DMI ratio by 17%, final body weight (FBW) by 7%, and empty body weight (EBW) by 4%. Additionally, the cooling loss was reduced by 13%. However, they did not observe any effects on carcass characteristics and meat quality. Martinez-Aispuro et al. [9] reported that lambs fed CaPr for 42 d at a daily dose of 13.9 g/lamb/d increased the FBW, ADG, ADG:DMI ratio, and without effects in DMI, longissimus muscle area (LMA), or fat thickness (FT). Furthermore, Cifuentes-López et al. [21] fed CaPr in the diet of growing lambs for 42 d, observed an improvement in dressing, carcass conformation, and LMA, with a reduction in adipose tissue, perirenal fat, and FT; however, they did not observe differences in the meat pH, DMI and ADG. In contrast, Lee-Rangel et al. [22] did not observe differences in DMI, ADG, ADG:DMI ratio, LMA or hot carcass weight (HCW) in growing lambs fed CaPr for 42 d. Based on the previous results, we determined that the inclusion of CaPr in the diet of feedlot ram lambs, to increase dietary energy, has always been supplied for 42 d before slaughter, ignoring whether that period is the right optimum.

We hypothesized that increasing dietary energy with CaPr in finishing lambs during the appropriate inclusion period improves growth performance, carcass characteristics, and meat quality in finishing lambs. Therefore, the present study proposed to determine the optimal inclusion period (0, 14, 28, or 42 d) of CaPr at a dose of 10 g/lamb/d on growth performance, carcass characteristics, and meat quality of finishing lambs.

2. Materials and Methods

The experiment was carried out in the Small Ruminant Experimental Center, the slaughter in an abattoir and the carcass quality measurements in the Meat Science and Technology Laboratory, all in the Unidad Académica de Medicina Veterinaria y Zootecnia, Universidad Autónoma de Zacatecas (UAMVZ-UAZ), located in state Zacatecas, Mexico (22° N and 102° W). The experiment was carried out during the months of August to September 2022, with a maximum temperature of 28 °C and a minimum of 8 °C.

Protocols, management, and animal care procedures were in agreement with the Bioethics and Animal Welfare Committee of UAMVZ-UAZ and adhered to the Official Mexican Standards NOM-024-ZOO-1995 [23]; NOM-033-SAG/ZOO-2014 [24]; NOM-051-ZOO-1995 [25], and NOM-062-ZOO (1999) [26].

2.1. Animals, Housing, and Management

Thirty-six Dorper × Katahdin crossbred ram lambs, with an average body weight of 39.1 ± 0.44 kg and 5.5 months of age, were individually housed in 1.5 m × 1.5 m pens equipped with individual feeders and provided with fresh water using the free choice method. Before entry to the feedlot, all animals were treated for internal (Closantel 5%) and external parasites (Doramectina 1%) and received an intramuscular injection of bacterin-toxoid (for *Clostridium* spp.). During the next two weeks, the ram lambs adapted to the finishing basal diet (Table 1), and we also monitored their health status.

Table 1. Ingredients and nutritional composition of the basal diet (dry matter basis).

Ingredients	g kg^{-1} DM
Alfalfa hay	100.0
Oats hay	102.0
Dry-rolled corn	460.0
Dried distillers grains	129.0
Soybean meal 44% CP	127.0
Molasses cane	43.0
Calcium carbonate	11.0

Table 1. *Cont.*

Ingredients	g kg^{-1} DM
Sodium bentonite	10.0
Sesquicarbonate	17.0
Microminerals [a]	0.5
Vitamins [b]	0.5
Chemical composition, g kg^{-1} DM	
Dry matter	842.8
Crude protein	163.0
Ether extract	24.0
Neutral detergent fiber	217.0
Calcium [c]	8.3
Phosphorus [c]	2.7
Ca:P ratio	3.1
Calculated net energy, Mcal/kg	
Maintenance	2.0
Gain	1.3

[a] Microminerals: Co (0.5 g), Fe (50 g), I (2.5 g), Mn (50 g), Zn (50 g), Se (0.2 g) y Cu (15 g). Excipient q.s.1000 g. [b] Vitamins A (5,000,000 IU), D (2,000,000 IU) y E (10,000 IU). Excipient q.s.1000 g. [c] Calculated values from NRC (2007) feed composition tables [27].

2.2. Treatments and Experimental Design

Lambs were randomly assigned to one of the following treatments (n = 9 lambs per treatment): (1) Basal diet without CaPr before slaughter, (2) Basal diet + 10 g/lamb/d 14 d before slaughter, (3) Basal diet + 10 g/lamb/d 28 d before slaughter, and (4) Basal diet + 10 g/lamb/d 42 d before slaughter. The CaPr used in the study was Nuprocal ™ (Nutryplus, Mexico), which provides an energy contribution similar to that of propionic acid, with an estimated gross energy of 3.965 Mcal/kg and a metabolizable energy (ME) of 3.766 Mcal/kg [15]. Individual CaPr doses were weighed on a certified scale (Pioneer-PX523, Ohaus Corp., Parsippany, NJ, USA) and mixed with 100 g of a basal diet. The treatments were offered individually during the morning feeding with careful observation to ensure their total intake. The remainder of the basal diet was administered immediately afterward.

Samples of the basal diet were taken daily and analyzed in a triplicate proportion for the following: dry matter (DM, dried for 24 h at 100 °C in a forced-air oven), crude protein (CP, FP-528 LECO nitrogen analyzer) [28], neutral detergent fiber (fiber Ankom analyzer), and ether extract (extractor of Ankom^{xt15}). Net energy for maintenance (NE_m) and net energy for gain (NE_g) of diets were calculated according to the equations [27]: NE_m (Mcal/kg of DM) = 1.37 ME − 0.138ME^2 + 0.0105ME^3 − 1.12, and NE_m (Mcal/kg of DM) = 1.42 ME − 0.174ME^2 + 0.0122ME^3 − 1.65.

2.3. Growth Performance and Ultrasound Measurements

Individual body weight was recorded at 0700 h before the morning feeding on d 0 (initial body weight, IBW), 14, 28, and 42 (FBW) d during the experiment. The diet offered and refusals were weighed and recorded daily. DM was used to estimate DMI (feed intake multiplied by the percentage of DM). Ad libitum feeding was offered with two daily meals (8:00 and 16:00 h). The diet amount offered was adjusted daily (as-feed basis), increasing by 5% from the consumption recorded the previous day. The ADG:DMI ratio was calculated as the ADG divided by the corresponding DMI. Fat thickness (FT) and longissimus muscle area (LMA) measurements were obtained from the longissimus muscle (LM) at 5 cm lateral to the middle line and between the 12th and 13th ribs using a real-time ultrasound (Aloka, Prosound 2, Tokyo, Japan) equipped with a 3.5 MHz linear transducer.

2.4. Slaughter Procedure

At the end of the 42 d feeding period, lambs underwent solid fasting for 18 h before being transported to the UAMVZ-UAZ abattoir at 0700 h. Immediately before slaughter, lambs were weighed (pre-slaughter BW). Slaughter procedures were under approved human methods by Mexican Official Standard NOM-033-SAG/ZOO-2014 [24].

2.5. Organ Mass

Non-carcass components, skin, complete gastrointestinal tract and digesta-free, heart, lungs, liver, spleen, kidney, and perirenal fat, were removed immediately after slaughter and weighed. The weights were expressed as grams per kilogram of empty body weight (EBW). The EBW was calculated by deducting the total non-carcass component weight from the pre-slaughter BW.

2.6. Carcass Characteristics

After evisceration, the carcasses (including kidneys and internal fat) were weighed to obtain the hot carcass weight (HCW) and chilled at 4 °C for 24 h. After the chilling period, the carcasses were reweighed to obtain cold carcass weight (CCW). In addition, carcass dressing ([CCW/EBW] × 100), and cooling loss ([HCW-CCW]/HCW) × 100 were calculated. After chilling, the carcasses were measured with a flexible tape measure to obtain carcass length, leg length, and chest circumference.

2.7. Whole Cuts and Tissue Composition

The right sides of the carcasses were cut to obtain the following whole cuts: forequarter, hindquarter, shoulder, leg, loin, rack, short rib, flank, breast, and neck, following the guidelines of the North American Meat Processors Association [29]. The yield of each cut was calculated by expressing its respective weight or as a percentage of the CCW. Carcasses were split in half, and the left side was dissected. The tissue composition of the shoulder was determined through physical dissection to calculate the percentage of muscle, fat, and bone.

2.8. Meat Characteristics

Muscle samples were collected from the cold carcass longissimus muscle (LM, approximately 500 g) and frozen at 20 °C for later analysis of meat quality. The meat color was measured by triplicate (and averaged) on the surface of the LM cut between rib 12th and 13th rib using a spectrophotometer Minolta CR-400 (Konica Minolta Sensing, Inc., Osaka, Japan; measuring aperture 8 mm, D65 illuminant, 2° observer angle, SCE mode). With the values of L* = lightness (0 = black, 100 = white); a* = red to green (positive values = red, negative values = green); b* = yellow to blue (positive values = yellow, negative values = blue). The pH obtained after chilling the carcass (24 h at 4 °C) was measured between the first and second lumbar vertebrae (LM), using a portable pH meter (Hanna Instruments, HI–9025).

The water-holding capacity (WHC) was quantified following the methodology described by Grau and Hamm, as proposed by Tsai and Ockerman [30]. Briefly, 300 mg of LM were covered with filter papers (Whatman #1), placed between glass plates (15 cm × 15 cm), and pressed under 10 kg at constant pressure for 20 min. LM steaks (2 cm-thick) obtained between the 12th rib and L2 vertebrae were vacuum-packed in plastic bags and frozen at −20 °C. After 14 d of storage, steaks were tempered for 24 h at 4 °C, blotted dry, and weighed. The weights taken before and after opening the vacuum packages were used to calculate purge loss. Steak samples (15 to 20 g) were used to determine cook loss (weight loss after cooking). Sealed plastic bag samples were individually placed and plunged in a water bath at 75 °C until reaching an internal temperature of 70 °C. Once cooked, the samples were cooled under running tap water, removed from the packaging, blotted, and weighed. WHC, purge loss, and cook loss were expressed as a percentage of weight loss relative to the initial weight, calculated as [(initial weight − final weight)/initial weight] × 100.

Warner–Bratzler shear force (WBSF) was measured by cooking steak samples in electric grills (model GR2120B, George Foreman Electronics) until they reached an internal temperature of 70 °C [31]. Once cooked, the steaks were cooled at room temperature (20–25 °C). Three samples from each steak were obtained (parallel to the muscle fiber) and sheared perpendicularly to the muscle fiber using a slice shear force blade mounted in a Warner-Bratzler shear machine (G-R Manufacturing, New York, NY, USA) at the crosshead speed of 200 mm/minute. Shear force measurements were averaged and expressed in kg/cm^2.

2.9. Statistical Analyses

Statistical analysis was carried out with SAS University software. Normality assumptions were confirmed using the UNIVARIATE procedure. Data were analyzed using a completely randomized design with the GLM procedure, except for ADG, DMI, and ADG:DMI ratio which were analyzed using the MIXED procedure for repeated measurements. Lamb and carcass were the experimental units for growth performance and meat characteristics. CCW was included as covariates for the analysis of carcass characteristics. Levels of CaPr supplementation were partitioned into linear and quadratic orthogonal polynomials, considering four equally spaced levels with the LSMEANS and ESTIMATE statements. When the quadratic polynomials were significant, the quadratic equations were calculated using the REG procedure. Significance was stated when the p-value was $\leq$0.05 and tendency when the p-value was >0.05 and $\leq$0.10.

3. Results and Discussion

3.1. Growth Performance and Ultrasound Measurements

Compared to Controls, lambs supplemented with CaPr showed greater (p < 0.01) FBW, ADG, and ADG:DMI ratio (Table 2) without effects on DMI (p = 0.73). The growth performance augmented quadratically (p < 0.05), being maximal at an estimated (from calculated equations) inclusion period of 25 d for FBW and ADG, 15 d for DMI, and 28 d for ADG:DMI ratio, with increments of 4.7, 26.8, 1.1, and 25.8% for the FBW, ADG, DMI, and ADG:DMI ratio, respectively.

Table 2. Growth performance of finishing lambs fed calcium propionate (CaPr) at different periods.

Item [b]	Days in CaPr [a]				SEM [c]	Effects (p-Value)		CaPr vs. Control
	0	14	28	42		Linear	Quadratic	
IBW, kg	39.5	39.1	39.4	38.6	0.44	0.27	0.71	0.39
FBW, kg	49.2	50.4	51.5	49.5	0.55	0.35	0.01	0.05
ADG, g/d	226.87	269.8	287.7	259.5	13.28	0.06	0.01	0.01
DMI, g/d	1419.1	1437.5	1435.0	1354.5	25.37	0.10	0.05	0.73
ADG:DMI ratio	0.16	0.19	0.20	0.19	0.01	0.09	0.05	0.01

[a] Treatments consisted of oral administration of CaPr (Nuprocal™, Nutryplus, Mexico) at a dose of 10 g/lamb/d at four feeding periods of 0, 14, 28, or 42 d before slaughter. [b] IBW = initial body weight, FBW = final body weight, ADG = average daily gain, DMI = dry matter intake. [c] SEM = standard error of the mean. FBW $y = -0.0043x^2 + 0.2164x + 48.28$ (R^2 = 0.998), maximal value at 25 d of inclusion. ADG $y = -0.0907x^2 + 4.6376x + 225.82$ (R^2 = 0.988), maximal value at 26 d of inclusion. DMI $y = -0.1261x^2 + 3.8961x + 1416.2$ (R^2 = 0.9641), maximal value at 15 d of inclusion. ADG:DMI ratio $y = -0.00006x^2 + 0.0034x + 0.1577$ (R^2 = 0.995), maximal value at 28 d of inclusion.

Previous reports demonstrate that increasing dietary energy consistently improves the growth performance of finishing lambs [2,17–19]. In that respect, it has been shown that CaPr dissociates in the rumen into propionate and calcium ions, raising energy status through a greater glucose synthesis in the liver [20]. Moreover, this compound alters the pattern of ruminal volatile fatty acid (VFA), reduces methane production, improves DM digestibility, and promotes fermentative efficiency [32–34].

Similar to our results, Martinez-Aispuro et al. [9] provided CaPr in diet to finishing Hampshire × Suffolk lambs (IBW 23.8 kg) and reported increments (p < 0.05) in FBW, ADG, ADG:DMI ratio, serum glucose, and ruminal propionate, but they observed no significant effects (p > 0.05) on DMI. The basal diet contained 66% grains and 2.5 Mcal/kg ME. Furthermore, Carrillo-Muro et al. [11] observed that the FBW, ADG, DMI, and ADG:DMI ratio were improved (p < 0.05) in Dorper × Katahdin (IBW 36.6 kg) lambs supplemented with CaPr (basal diet contained 59% grains and 2.8 Mcal/kg ME). In both studies, the CaPr was administered for a fixed time of 42 d before harvest and demonstrated the usefulness of CaPr in improving growth performance.

In contrast, other studies did not report significant differences ($p > 0.05$) in growth performance. Lee-Rangel et al. [22] did not observe differences in DMI, ADG, or ADG:DMI ratio of growing Criollo lambs (IBW 28.1 kg) fed CaPr mixed in the diet for 42 d (basal diet contained 55 or 65% grains) when compared to Control lambs. The authors assume that the amount of CaPr added to the diet in their study was insufficient to affect ADG. In addition, Mendoza-Martínez et al. [15] supplemented CaPr in the diet (57% concentrate and 2.5 Mcal/kg ME) of finishing Criollo lambs (IBW 25.3 kg) for 42 d. The authors did not observe differences in growth performance among treatments and attributed this phenomenon to the lack of effects on the ruminal VFA pattern (total and proportional VFA) of the lambs.

The reasons for inconsistencies among studies are not clear, given the various experimental conditions (dose, breed, initial weight, previous experimental conditions, diet quality, and energy content), since previous research showed that animal response to CaPr administration is affected by diverse factors such as roughage quality [35], dose [32], stage of growth period [36], grain content [22], age [37] and physiological status [16].

Previous studies in lambs have not thoroughly investigated the optimal length of CaPr supplementation. Nevertheless, the changes observed through periods in this study suggest a modification of the growth response over time ($p < 0.05$) with the use of CaPr being optimized when the supplementation period approaches 28 d and a slight reduction at 42 d of supplementation.

One possible explanation for the observed quadratic ($p < 0.05$) growth performance in the present study could be the slight reduction in DMI observed when feeding CaPr for 42 d, which may have affected other growth performance variables. However, the overall effect of CaPr inclusion on DMI (hypophagia) was not significant (CaPr vs. Control, $p = 0.74$), which is consistent with further reported studies in finishing ram lambs fed CaPr [9,11,21,22,38].

This reduction effect on DMI is known as hepatic oxidation theory (HOT) and was described by Allen [39] to explain the role of the ruminant liver in signaling and controlling satiety in ruminants through temporal patterns of oxidative fuels such as lactate, propionate, and non-esterified fatty acids (NEFAs). Signals are carried from the liver to the brain via afferents in the vagus nerve and are affected by hepatic oxidation and the generation of ATP. The effect was previously reported in ruminants due to constant and rapid VFA production with increased rumen propionate levels and raised available energy related to plasma glucose concentration [40,41]. However, a significant reduction in DMI due to the HOT effect was observed only when propionate was directly added directly to the rumen or infused into the portal vein [42–44].

3.2. Organ Mass, Ultrasound Measurements and Carcass Characteristics

CaPr supplementation significantly improved EBW compared to the control group ($p < 0.05$). Additionally, the EBW increased quadratically ($p < 0.05$) with the maximum value estimated at 28 d of inclusion based on the quadratic equations. However, the mass of the different organs was not affected ($p \geq 0.5$) (Table 3).

The ultrasound FT increased linearly ($p < 0.05$) with the inclusion period, while the LMA remained unaffected ($p > 0.05$) by the dietary CaPr administration. Additionally, lambs supplemented with CaPr showed significantly greater HCW, CCW, and dressing compared to the Control group ($p < 0.05$) (Table 4). The greatest responses (quadratic effect, $p < 0.05$) were reached within the inclusion period of 24 d for HCW and CCW and 20 d for dressing, with increments of 8.3, 8.5, and 4.2% for the HCW, CCW, and dressing, respectively. However, cooling loss, carcass measurements (carcass length, leg circumference, chest circumference) and shoulder composition (muscle, fat, and bone) were unaffected ($p > 0.05$) by the dietary CaPr administration.

Table 3. Organ mass of finishing lambs fed calcium propionate (CaPr) at different periods.

Item [b]	Days in CaPr [a]				SEM [c]	Effects (*p*-Value)		CaPr vs. Control
	0	14	28	42		Linear	Quadratic	
Empty BW, kg	40.9	42.7	42.9	42.7	0.71	0.1	0.04	0.05
Skin	158	142	159	170	8.61	0.2	0.16	0.89
Limbs	26.5	25.3	27.6	24.4	1.42	0.56	0.54	0.7
Head	41.9	42.9	39.1	42.4	0.98	0.62	0.31	0.75
Heart	5.4	5.6	4.8	5.7	0.38	0.9	0.5	0.96
Lungs	23.3	22.2	22.1	23.7	1.73	0.9	0.5	0.77
Liver	22.5	21.6	21	19.4	2.43	0.39	0.91	0.56
Spleen	2.8	2.6	2.3	2.7	0.38	0.65	0.52	0.54
Kidney	3.1	3	2.8	3.1	0.15	0.68	0.2	0.37
Testicles	20.3	17.8	15.8	18	1.32	0.16	0.13	0.08
Visceral fat	36.5	49.5	37.5	32.6	5.5	0.36	0.16	0.62
Perirenal fat	13.8	17.5	14.5	12.6	3.1	0.64	0.41	0.78
Stomach [d]	31.6	27.8	29.9	31.9	1.7	0.68	0.13	0.42
Large intestine	11.2	9.7	10.2	10.4	1.1	0.7	0.47	0.42
Small intestine	19.1	17.6	19.6	20.3	1.1	0.26	0.38	0.92

[a] Treatments consisted of oral administration of CaPr (Nuprocal^{TM}, Nutryplus, Mexico) at a dose of 10 g/lamb/d at four feeding periods of 0, 14, 28, or 42 d before slaughter. [b] Non carcass components are expressed in g/kg of empty body weight. [c] SEM = standard error of the mean. [d] Includes the rumen-reticulum, omasum, and abomasum. Empty BW $y = -0.0026x^2 + 0.1471x + 40.96$ ($R^2 = 0.9727$), maximal value at 28 d of inclusion.

Table 4. Ultrasound measurements, carcass characteristics, and shoulder composition of finishing lambs fed calcium propionate (CaPr) at different periods.

Item [b]	Days in CaPr [a]				SEM [c]	Effects (*p*-Value)		CaPr vs. Control
	0	14	28	42		Linear	Quadratic	
				Ultrasound measurements				
Fat thickness, mm	3.0	3.5	3.6	3.9	0.23	0.01	0.78	0.02
LMA, cm^2	12.5	12.6	13.2	12.0	0.47	0.68	0.2	0.88
				Carcass characteristics				
HCW, kg	23.3	25.4	24.9	24.4	0.4	0.2	0.01	0.01
CCW, kg	22.5	24.6	24.1	23.6	0.5	0.18	0.02	0.01
Dressing, %	55.2	57.6	56.2	55.4	0.5	0.77	0.01	0.05
Cooling loss, %	3.40	2.71	3.04	2.95	0.237	0.44	0.22	0.08
Carcass length, cm	70.09	67.32	70.79	67.52	1.60	0.74	0.88	0.42
Leg circumference, cm	45.90	45.24	43.97	43.89	1.55	0.29	0.86	0.40
Chest circumference, cm	76.8	79.3	76.3	78.3	1.23	0.88	0.53	0.61
				Shoulder composition				
Muscle, %	66.47	66.51	65.22	64.71	1.10	0.18	0.81	0.44
Fat, %	14.17	15.18	16.05	16.33	1.25	0.19	0.77	0.25
Bone, %	19.36	18.32	18.73	18.95	0.504	0.81	0.23	0.25

[a] Treatments consisted of oral administration of CaPr (Nuprocal^{TM}, Nutryplus, Mexico) at a dose of 10 g/lamb/d at four feeding periods of 0, 14, 28, or 42 d before slaughter. [b] LMA = longissimus muscle area, HCW = hot carcass weight, CCW = cold carcass weight. [c] SEM = standard error of the mean. HCW $y = -0.0033x^2 + 0.1593x + 23.43$ ($R^2 = 0.8603$), maximal value at 24 d of inclusion. CCW $y = -0.0033x^2 + 0.1593x + 22.63$ ($R^2 = 0.8603$), maximal value at 24 d of inclusion. Dressing $y = -0.0041x^2 + 0.1657x + 55.42$ ($R^2 = 0.7281$), maximal value at 20 d of inclusion.

Previous studies using CaPr as a gluconeogenic precursor in fattening lambs reported an inclusion period of 42 d before slaughter as a common rule and generally at higher doses than those used in this study. Martínez-Aispuro et al. [9] observed an improvement ($p < 0.05$) in the FBW of wool lambs at a CaPr daily dose of 13.9 g/lamb/d (average of 0.46 g/kg BW) for 42 d but observed no effect ($p > 0.05$) on LMA or FT. Furthermore, Lee-Rangel et al. [22] fed CaPr in the diet at 12 g/lamb/d (average of 0.36 g/kg BW), while Mendoza-Martinez et al. [15] fed CaPr at 11.7 and 25.9 g/lamb/d (average of 0.40 and 0.87 g/kg BW), in both studies lambs were fed CaPr for 42 d; however, neither study reported differences ($p > 0.05$) in HCW or LMA (CaPr vs. Control) of male Criollo lambs. Conversely, Cifuentes-López et al. [21] fed CaPr at high doses of 30, 35, and 40 g/kg DM (equivalent to 1.33, 1.65, 1.83 g/kg BW) in the diet of growing Rambouillet lambs (28.1 kg of IBW) for 42 d. They observed improvements ($p < 0.05$) in dressing, carcass conformation, and LMA, along with reductions ($p < 0.05$) in adipose tissue, perirenal fat, and FT, but no differences ($p > 0.05$) in organ weights (reported as rumen and intestines, and viscera and integuments). Additionally, Carrillo-Muro et al. [11] fed CaPr to crossbreed (Dorper x Katahdin) finishing lambs (35 kg BW) to test doses of 10, 20, and 30 g/lamb/d, with the greatest response observed at a dose of 20 g/lamb/d (0.49 g/kg BW). They reported that EBW, heart weight, and small intestine weight increased ($p < 0.03$) in lambs fed CaPr, with a tendency ($p < 0.07$) to augment liver mass, but no effects ($p \geq 0.43$) on other organ mass. Moreover, the authors reported increases in HCW ($p = 0.09$) and CCW ($p = 0.08$) and a lower cooling loss ($p < 0.05$), but they found no significant effects ($p < 0.05$) on dressing percentage, pH, carcass measurements, or the tissue composition. The authors of both studies related their results to the energy enhancement promoted by CaPr supplementation.

The positive effects of increased energy levels in the diet on carcass characteristics of finishing lambs have been demonstrated previously by Piola-Junior et al. [45] who reported a linear relationship between dietary ME density (2.0, 2.3, 2.5, 2.8 Mcal/kg) and the slaughter BW ($R^2 = 0.95$), HCW ($R^2 = 0.96$), CCW ($R^2 = 0.95$), and dressing ($R^2 = 0.91$) in crossbred Ile de France ram lambs (7.9 months of age, IBW 26.6 kg) fed with iso-protein diets. In addition, Moloney conducted a study to determine if isoenergetic (2.9 Mcal/kg ME) and isonitrogenous (16.5% CP) rations with different ruminal fermentation patterns (inclusion of sodium propionate at 0 or 40 g/kg) altered the growth and carcass composition in ram lambs. The authors observed a decrease in fat deposition, an increase in skeletal muscle growth, and an altered ratio of acetate to propionate in ruminal fluid from the effect of adding sodium propionate to the diet. They attributed the increase in protein accumulation to absorbed propionate, which is used for gluconeogenesis, thus sparing amino acids to increase protein synthesis.

The increase in energy availability offered by gluconeogenic precursors explains the observed increments in EBW, FT, and carcass weight. However, the lack of differences in the rest of the evaluated characteristics reflects that the level of CP and energy provided in the diet used in this study (16.3% CP, 2.8 Mcal/kg ME and 1.3 NE_g, Mcal/kg) was adequate for finishing Dorper crossbred lambs. The results of the present study agree with Deng et al. [46] since they estimated that Dorper crossbred lambs need a range between 0.267 and 1.27 Mcal/d NE_g for ADG of 100 to 400 g.

Under the conditions of this study, the EBW, carcass weight, and dressing were optimized (maximal values calculated from regression equations) when the supplementation period was approximately 28, 24, and 20 d, respectively (quadratic effect, $p < 0.05$). In addition, a longer inclusion period favored an increase in ultrasound FT (linear effect, $p < 0.05$) which is expected because of the greater energy available. Therefore, to improve carcass weight without increasing TF, it is recommended to administer CaPr for a maximum of 28 d and not for 42 d, which is the inclusion period commonly reported in this literature.

3.3. Whole Cuts

As shown in Table 5, the CaPr administration improves (CaPr vs. Control, $p < 0.03$) the forequarter, leg, rack, and neck cuts (g/kg of EBW). At 28 d of CaPr inclusion, greater weight (quadratic effect, $p < 0.04$) in the forequarter (g/kg of EBW) and the neck (expressed as both g/kg of EBW and as a percentage of CCW) was observed. However, for 14 to 42 d of CaPr inclusion, greater rack weight (linear effect, $p < 0.04$) was appreciated, in addition, the more extended inclusion period reduced the loin as a percentage of CCW (linear effect, $p < 0.03$).

Table 5. Whole cuts of finishing lambs fed calcium propionate (CaPr) at different periods.

Item [b]	Days in CaPr [a]				SEM [c]	Effects (*p*-Value)		CaPr vs. Control
	0	14	28	42		Linear	Quadratic	
			Whole cuts, g/kg of EBW					
Forequarter	5.7	6.3	6.4	6.1	0.18	0.14	0.04	0.03
Hindquarter	5.3	5.6	5.6	5.4	0.19	0.71	0.17	0.28
Shoulder	2	2	2.1	2	0.06	0.78	0.25	0.48
Shoulder IMPS206	1.1	1	1	1.1	0.11	0.94	0.51	0.65
Leg IMPS233	2.9	3.2	3.2	3.2	0.09	0.02	0.37	0.02
Loin IMPS231	1.5	1.4	1.5	1.3	0.07	0.12	0.43	0.31
Rack IMPS204	0.7	0.8	0.8	0.8	0.02	0.02	0.02	0.001
Short rib	0.7	0.7	0.7	0.6	0.05	0.7	0.21	0.6
Flank IMPS232	0.8	0.9	0.9	0.9	0.04	0.21	0.3	0.09
Breast	0.8	0.9	1	0.9	0.06	0.23	0.22	0.12
Neck	0.7	0.9	1	0.8	0.07	0.26	0.01	0.03
			Whole cuts, as percentage of cold carcass weight (CCW)					
Forequarter	51.2	51.2	53.4	51.8	0.66	0.44	0.57	0.51
Hindquarter	46.6	45.4	46.4	45.2	0.75	0.68	0.98	0.65
Shoulder	17.4	16.4	17.2	16.6	0.25	0.54	0.7	0.3
Shoulder IMPS206	9.8	8.4	8.4	9.2	0.4	0.67	0.2	0.28
Leg IMPS233	25.6	25.6	26.2	27.4	0.4	0.1	0.5	0.4
Loin IMPS231	13.4	11.6	12.4	11	0.28	0.03	0.83	0.04
Rack IMPS204	6.2	6.6	6.4	6.6	0.05	0.09	0.6	0.07
Short rib	5.8	6	5.8	5.4	0.18	0.39	0.46	0.81
Flank IMPS232	7	7.4	7.2	7.6	0.19	0.43	0.9	0.44
Breast	7.2	7.4	8	7.8	0.25	0.39	0.63	0.41
Neck	5.8	7.2	8.2	6.4	0.32	0.4	0.04	0.1

[a] Treatments consisted of oral administration of CaPr (Nuprocal™, Nutryplus, Mexico) at a dose of 10 g/lamb/d at four feeding periods of 0, 14, 28, or 42 d before slaughter. [b] Whole cuts are expressed in g/kg of empty body weight and percentage of cold carcass weight. [c] SEM = standard error of the mean. Forequarter g/kg of EBW $y = -0.0011x^2 + 0.0575x + 5.705$ ($R^2 = 0.9983$), maximal value at 26 d of inclusion. Rack IMPS204, g/kg of EBW $y = -0.0001x^2 + 0.0075x + 0.705$ ($R^2 = 0.9333$), maximal value at 36 d of inclusion. Neck, g/kg of EBW $y = -0.0005x^2 + 0.0243x + 0.69$ ($R^2 = 0.96$), maximal value at 24 d of inclusion. Neck as percentage of CCW $y = -0.0041x^2 + 0.1914x + 5.68$ ($R^2 = 0.9111$), maximal value at 24 d of inclusion.

No previous information was found about the effect of CaPr on the whole cuts of lambs since the authors did not report these measurements in the available literature. In addition, information on other gluconeogenic precursors fed to ruminants on whole cuts is scarce. A study conducted by Gomes et al. [47] evaluated the influence of diets supplemented with glycerin, as an alternative ingredient to corn on Santa Inês confined lambs (IBW 26.33 kg) with diets (40% roughage and 60% concentrate) containing 0, 15 or 30% glycerin in the total feed, and slaughtered with an average live weight of 34 to 36 kg. The authors did not report effects ($p > 0.05$) of the gluconeogenic precursors on final live weight and carcass weight and neither observed any effect on the percentage of whole cuts.

Otherwise, Shadnoush et al. [48] evaluated the effect of three slaughter weights (45, 52.5, and 60 kg) and two energy levels in the diet (2.64 and 2.4 Mcal/kg ME) on carcass characteristics of the Lori-Bakhtiari ram lambs (IBW 35.7 kg). They reported that high-energy diets increased ($p < 0.05$) shoulder weight but did not affect ($p > 0.05$) neck, leg, back, or tail fat weight. Furthermore, as slaughter weight increased, all cuts except the neck showed a greater weight and denoted a faster maturation of the head than the rest of the whole cuts.

Lamb carcass tissue growth is influenced by multiple factors such as breed, sex, carcass weight, type of delivery, and rearing [49,50]. In this regard, Bradford and Spurlock [51] reported that ram lambs (as the animals used in the present study) had a higher percentage of carcass weight in the forequarters than whether lambs. However, whole cuts are mainly affected by the plane of nutrition.

Furthermore, Owens et al. [52] stated that organs and tissues mature at different relative growth rates, with an apparent general gradient in organ/muscle formation from head to tail and from extremities to the core. Relative growth or tissue maturation is affected by age and growth rate (gain in weight per unit of time). However, the general sequence of body maturation is head, metatarsus, and kidney fat first; followed by the neck, bone, tibia-fibula, and intramuscular fat; later the thorax, muscle, femur, and subcutaneous fat and finally, the loin, pelvis, and intramuscular fat. Therefore, animals with similar ages but different growth rates influenced by diet possibly show different tissue maturation and relative growth.

Based on the above, we can infer that the changes observed in the values of the whole cuts result from an increase in general body weight and differential tissue growth promoted by the rise in the growth rate due to CaPr supplementation in lambs of the same breed and age. The results could imply the possibility of increasing the weight of the highest value cuts by providing CaPr in a different inclusion period; for example, providing CaPr for 28 d to enlarge the weight of forequarter, or for only 14 d if we are interested in maximizing the weight of the Leg IMPS233 or Rack IMPS204 cuts; however, this possibility could be the subject of future research.

3.4. Meat Characteristics

Regardless of the inclusion period, dietary CaPr supplementation did not affect ($p > 0.05$) purge loss, cook loss, WHC, WBFS, or color (L*, a*, and b* values) (Table 6). However, CaPr administration increased (CaPr vs. Control, $p < 0.01$) overall muscle pH values, which also increased linearly as the inclusion period became longer ($p < 0.02$).

Table 6. Meat characteristics and meat color of finishing lambs fed calcium propionate (CaPr) at different periods.

Item [b]	Days in CaPr [a]				SEM [c]	Effects (*p*-Value)		CaPr vs. Control
	0	14	28	42		Linear	Quadratic	
				Meat characteristics				
pH_{24h}	5.2	5.6	5.7	5.7	0.15	0.02	0.24	0.01
Purge $loss_{24h}$, %	5	3.9	6	5	0.73	0.66	0.7	0.67
Cook loss, %	26.4	22.3	22.6	24.4	2.6	0.62	0.28	0.29
WHC, %	23.3	23	24.9	21.1	2.3	0.65	0.47	0.9
WBSF, kg/cm^2	5	4.4	4.9	4.7	0.19	0.74	0.38	0.2
				Color				
L*	44.1	43.7	46.3	43.5	1.75	0.91	0.5	0.83
a*	17.8	17.2	17	16.9	0.89	0.48	0.84	0.49
b*	6.1	6.5	6.2	5.1	0.61	0.23	0.26	0.76

[a] Treatments consisted of oral administration of CaPr (Nuprocal[TM], Nutryplus, Mexico) at a dose of 10 g/lamb/d at four feeding periods of 0, 14, 28, or 42 d before slaughter. [b] Meat characteristics were measured on the longissimus muscle between the 12th rib and the 2nd lumbar vertebrae. WHC = water-holding capacity, WBSF = Warner-Bratzler shear force. [c] SEM = standard error of the mean.

Meat quality is principally affected by temperature cooling and pH in the post-mortem period being involved in tenderness, WHC and color [53]. The ideal pH value has been established between 5.5 and 5.8 since adequate proteolysis of myofibrillar proteins occurs in this range, in addition to the reversal of rigor mortis and improvement of meat tenderness [54]. pH values higher than 5.8 significantly increase shear force values [55] and decrease acceptance scores of meat by consumers such as aroma, flavor, juiciness, texture, and tenderness [56].

An explanation for the greater pH values observed in meat from lambs fed CaPr than the Control lambs is uncertain. However, the CaPr treatment values remained within the ideal pH values (5.5 and 5.8), contrary to the Control treatment that obtained lower values than the ideal. In this regard, Stewart et al. [57] carried out a study to test the associations between the plasma stress indicators and lamb ultimate pH, observing a significant positive association between the plasma glucose concentration and the pH at 24 h post-mortem ($p < 0.01$), and as plasma glucose concentration increased from 2 mmol/L to 10 mmol/L, the pH increased by 0.16 pH units from 5.60 to 5.76.

In the present study, the blood glucose level was not measured. However, it is well known that dietary CaPr is dissociated in the rumen increasing the ruminal propionate proportion that promotes glucose synthesis in the liver [20,58]. Therefore, it is plausible that the higher pH observed in meat could be attributed to an increase in blood glucose levels resulting from CaPr supplementation [9,40,59].

Similar to our results, other authors neither reported any effect of CaPr supplementation on purge loss, cook loss, WHC, or WBFS [11,60]. In addition, the WBSF values obtained in the present study were less than the 5.0 kg/cm^2 value established by Hopkins et al. [61] as the upper limit value to consider lamb meat tenderness by consumers.

A fresh appearance and light color are preferred attributes by traditional lamb meat consumers [62]; however, these preferences depend on cultural issues and regionalism [63]. Meat color is affected by animal nutrition, carcass cooling rate, muscle pH, storage time, oxygen exposure, and myoglobin content [64,65].

In agreement with our results, Piao et al. [66] did not observe changes ($p < 0.05$) in the instrumental color of steers supplemented with glycerol in replacement of dietary grains. However, contrary to the results of the present study, Carrillo-Muro et al. [11] observed that in lambs fed CaPr, the L* (lightness) value was reduced ($p < 0.001$), but a* and b* values increased ($p < 0.001$) at 30 g/lamb/d.

Based on the previous results, we can suggest that including CaPr in the diet of finishing lambs for 14 d at a dose of 10 g/lamb/d is sufficient to improve the meat pH value, approaching the ideal values that enhance quality attributes. However, it is noteworthy that the improvement in pH values did not lead to alterations in meat quality characteristics such as purge loss, cook loss, WHC, WBFS, or color.

4. Conclusions

We concluded that CaPr is a useful feed additive that provides an additional energy source for finishing lambs. Under the current experimental conditions, the optimal inclusion period was 24 to 28 d because maximized most growth performance (FBW, ADG, and ADG:DMI ratio), carcass characteristics (HCW, CCW, carcass dressing, EBW), and some whole cuts (forequarters and neck), without affecting organ mass or meat quality.

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Data Availability Statement: If required, the corresponding author can provide the database.

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References

1. Teixeira, A.B.M.; Schuh, B.R.F.; Daley, V.L.; Pinto, P.H.N.; Fernandes, S.R.; de Freitas, J.A. Performance, biochemical and physiological parameters of Dorper× Santa Ines lambs fed with three levels of metabolizable energy. *Trop. Anim. Health Prod.* **2021**, *53*, 353. [CrossRef] [PubMed]
2. Wang, Y.; Wang, Q.; Dai, C.; Li, J.; Huang, P.; Li, Y.; Ding, X.; Huang, J.; Hussain, T.; Yang, H. Effects of dietary energy on growth performance, carcass characteristics, serum biochemical index, and meat quality of female Hu lambs. *Anim. Nutr.* **2020**, *6*, 499–506. [CrossRef] [PubMed]
3. Huntington, G.B. Starch utilization by ruminants: From basics to the bunk. *J. Anim. Sci.* **1997**, *75*, 852–867. [CrossRef]
4. Lawrence, J.D.; Mintert, J.R.; Anderson, J.D.; Anderson, D.P. Feed grains and livestock: Impacts on meat supplies and prices. *Choices* **2008**, *23*, 11–15.
5. Suh, D.H.; Moss, C.B. Decompositions of corn price effects: Implications for feed grain demand and livestock supply. *Agric. Econ.* **2017**, *48*, 491–500. [CrossRef]
6. Valente, T.N.P.; Sampaio, C.B.; Lima, E.D.S.; Deminicis, B.B.; Cezario, A.S.; Santos, W.B.R.D. Aspects of acidosis in ruminants with a focus on nutrition: A review. *J. Agric. Sci.* **2017**, *9*, 90–97. [CrossRef]
7. Stock, R.; Britton, R.; Acidosis in feedlot cattle; Parrott, C. Secondary benefits from feeding Rumensin. In *Scientific Update on Rumensin/Tylan for the Professional Feed-Lot Consultant*; Elanco Animal Health: Indianapolis, IN, USA, 1993; pp. A1–A13.
8. Galyean, M.L.; Perino, L.J.; Duff, G.C. Interaction of cattle health/immunity and nutrition. *J. Anim. Sci.* **1999**, *77*, 1120–1134. [CrossRef]
9. Martínez-Aispuro, J.; Sanchez-Torres, M.; Mendoza-Martínez, G.; Cordero Mora, J.; Figueroa-Velasco, J.; Ayala-Monter, M.; Crosby-Galvan, M. Addition of calcium propionate to finishing lamb diets. *Vet. Mex.* **2018**, *5*, 37–46. [CrossRef]
10. Cifuentes-Lopez, O.; Lee-Rangel, H.A.; Mendoza, G.D.; Delgado-Sanchez, P.; Guerrero-Gonzalez, L.; Chay-Canul, A.; Pinos-Rodriguez, J.A.; Flores-Ramírez, R.; Roque-Jimenez, J.A.; Relling, A.E. Effects of dietary calcium propionate supplementation on hypothalamic neuropeptide messenger RNA expression and growth performance in finishing rambouillet lambs. *Life* **2021**, *11*, 566. [CrossRef]
11. Carrillo-Muro, O.; Rivera-Villegas, A.; Hernández-Briano, P.; López-Carlos, M.A.; Aguilera-Soto, J.I.; Estrada-Angulo, A.; Medina-Flores, C.A.; Méndez-Llorente, F. Effect of calcium propionate level on the growth performance, carcass characteristics, and meat quality of feedlot ram lambs. *Small Rumin. Res.* **2022**, *207*, 106618. [CrossRef]
12. Saleem, A.M.; Singer, A.M. Growth performance and digestion of growing lambs fed diets supplemented with glycerol. *Animal* **2018**, *12*, 959–963. [CrossRef] [PubMed]
13. Ferraro, S.M.; Mendoza, G.D.; Miranda, L.A.; Gutiérrez, C.G. In vitro gas production and ruminal fermentation of glycerol, propylene glycol and molasses. *Anim. Feed Sci. Technol.* **2009**, *154*, 112–118. [CrossRef]
14. 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*, 29–39. [CrossRef]
15. Mendoza-Martínez, G.D.; Pinos-Rodríguez, J.M.; Lee-Rangel, H.A.; Hernández-García, P.A.; Rojo-Rubio, R.; Relling, A. Effects of dietary calcium propionate on growth performance and carcass characteristics of finishing lambs. *Anim. Prod. Sci.* **2016**, *56*, 1194–1198. [CrossRef]
16. 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*, 1336. [CrossRef]
17. Hosseini, S.M.; Akbary, S.M.; Maheri-Sis, N.; Aghsaghali, A.M. Effect of different energy levels of diet on feed efficiency, growth rate and carcass characteristics of fattening bahmaei lambs. *J. Anim. Vet. Adv.* **2008**, *7*, 1551–1554.
18. Papi, N.; Mostafa-Tehrani, A.; Amanlou, H.; Memarian, M. Effects of dietary forage-to-concentrate ratios on performance and carcass characteristics of growing fat-tailed lambs. *Anim. Feed Sci. Technol.* **2011**, *163*, 93–98. [CrossRef]
19. De Araújo Camilo, D.; Sales Pereira, E.; Guimarães Pimentel, P.; Lopes Oliveira, R.; Duarte Cândido, M.J.; Goes Ferreira Costa, M.R.; da Silva Aquino, R.M. Intake and feeding behaviour of Morada Nova lambs fed different energy levels. *Ital. J. Anim. Sci.* **2012**, *11*, e3. [CrossRef]
20. Aiello, R.J.; Armentano, L.E.; Bertics, S.J.; Murphy, A.T. Volatile fatty acid uptake and propionate metabolism in ruminant hepatocytes. *J. Dairy Sci.* **1989**, *72*, 942–949. [CrossRef] [PubMed]
21. Cifuentes-López, R.O.; Lee-Rangel, H.A.; García-Lopez, J.C.; Vicente, J.G.; Flores-Primo, A.; Pinos-Rodriguez, J.M. Effect of calcium propionate on live weight, consumption and carcass of lambs fed on alfalfa hay (*Medicago sativa*). *Agrociencia* **2018**, *52*, 81–88.
22. Lee-Rangel, H.A.; Mendoza, G.D.; Gonzalez, S.S. Effect of calcium propionate and sorghum level on lamb performance. *Anim. Feed Sci. Technol.* **2012**, *177*, 237–241. [CrossRef]
23. NOM-024-ZOO. Especificaciones y Características Zoosanitarias para el Transporte de Animales, sus Productos y Subproductos, Productos Químicos, Farmacéuticos Biológicos y Alimenticios Para uso en Animales o Consumo por Éstos. 1995. Available online: https://www.sinec.gob.mx/SINEC/ (accessed on 15 October 2022).
24. NOM-033-SAG/ZOO. Métodos Para dar Muerte a los Animales Domésticos y Silvestres. 2014. Available online: https://www.sinec.gob.mx/SINEC/ (accessed on 15 October 2022).
25. NOM-051-ZOO. Trato Humanitario en la Movilización de Animales. 1995. Available online: https://www.sinec.gob.mx/SINEC/ (accessed on 15 October 2022).

26. NOM-062-ZOO. Especificaciones Técnicas Para la Producción, Cuidado y uso de Animales de Laboratorio. 1999. Available online: https://www.sinec.gob.mx/SINEC/ (accessed on 15 October 2022).
27. National Research Council (NRC). *Nutrient Requirements of Small Ruminants: Sheep, Goats, Cervids, and New World Camelids*; The National Academies Press: Washington, DC, USA, 2007; p. 384.
28. AOAC (Official Methods of Analysis). *Official Methods of Analysis of AOAC International*, 20th ed.; AOAC: Rockville, MD, USA, 2016.
29. NAMP. *The Meat Buyers Guide*; North American Meat Processor Association: Weimar, TX, USA, 1997.
30. Tsai, T.C.; Ockerman, H.W. Water binding measurement of meat. *J. Food Sci.* **1981**, *46*, 697–701. [CrossRef]
31. AMSA. *Research Guidelines for Cookery, Sensory Evaluation, and Instrumental Tenderness Measurements of Meat*, 2nd ed.; American Meat Science Association: Champaign, IL, USA, 2016.
32. Liu, Q.; Wang, C.; Guo, G.; Yang, W.Z.; Dong, K.H.; Huang, Y.X.; Yang, X.M.; He, D.C. Effects of calcium propionate on rumen fermentation, urinary excretion of purine derivatives and feed digestibility in steers. *J. Agric. Sci.* **2009**, *147*, 201–209. [CrossRef]
33. Osorio-Teran, A.I.; Mendoza-Martínez, G.D.; Miranda-Romero, L.A.; Martínez-Gomez, D.; Hernández-García, P.A.; Martínez-García, J.A. Effect of calcium propionate and monensin on in vitro digestibility and gas production. *Rev. Bras. Zootec.* **2017**, *46*, 348–353. [CrossRef]
34. Murillo-Ortiz, M.; Pámanes-Carrasco, G.; Castillo, Y.; Ortiz-Robledo, F.; Herrera-Torres, E. Evaluation of monensin, yeast and glucogenic precursor on growth performance, ruminal fermentation and digestive kinetics of feedlot steers. *Indian J. Anim. Res.* **2019**, *B-1003*, 1–4. [CrossRef]
35. Villalba, J.J.; Provenza, F.D. Preference for flavored wheat straw by lambs conditioned with intraruminal administrations of sodium propionate. *J. Anim. Sci.* **1996**, *74*, 2362–2368. [CrossRef]
36. Zhang, X.; Wu, X.; Chen, W.; Zhang, Y.; Jiang, Y.; Meng, Q.; Zhou, Z. 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*, e0179940. [CrossRef]
37. Nocek, J.E.; Herbein, J.H.; Polan, C.E. Influence of ration physical form, ruminal degradable nitrogen and age on rumen epithelial propionate and acetate transport and some enzymatic activities. *Nutr. J.* **1980**, *110*, 2355–2364. [CrossRef]
38. Moloney, A.P. Growth and carcass composition in sheep offered isoenergetic rations which resulted in different concentrations of ruminal metabolites. *Livest. Prod. Sci.* **1998**, *56*, 157–164. [CrossRef]
39. Allen, M.S. Drives and limits to feed intake in ruminants. *Anim. Prod. Sci.* **2014**, *54*, 1513–1524. [CrossRef]
40. Allen, M.S.; Bradford, B.J.; Oba, M. Board-invited review: The hepatic oxidation theory of the control of feed intake and its application to ruminants. *J. Anim. Sci.* **2009**, *87*, 3317–3334. [CrossRef] [PubMed]
41. Oba, M.; Allen, M.S. Dose-response effects of intrauminal infusion of propionate on feeding behavior of lactating cows in early or midlactation. *J. Dairy Sci.* **2003**, *86*, 2922–2931. [CrossRef] [PubMed]
42. Bradford, B.J.; Gour, A.D.; Nash, A.S.; Allen, M.S. Propionate challenge tests have limited value for investigating bovine metabolism. *J. Nutr.* **2006**, *136*, 1915–1920. [CrossRef]
43. Farningham, D.A.H.; Whyte, C.C. The role of propionate and acetate in the control of food intake in sheep. *Br. J. Nutr.* **1993**, *70*, 37–46. [CrossRef] [PubMed]
44. Bradford, B.J.; Allen, M.S. Depression in feed intake by a highly fermentable diet is related to plasma insulin concentration and insulin response to glucose infusion. *J. Dairy Sci.* **2007**, *90*, 3838–3845. [CrossRef] [PubMed]
45. Piola Junior, W.; de Castro, F.A.B.; Bumbieris Junior, V.H.; da Silva, L.D.F.; Muniz, C.A.D.S.D.; Ribeiro, E.D.A. Effects of dietary energy level on the performance and carcass characteristics of lambs. *Semin. Ciências Agrárias.* **2020**, *41*, 2307–2316. [CrossRef]
46. Deng, K.D.; Diao, Q.Y.; Jiang, C.G.; Tu, Y.; Zhang, N.F.; Liu, J.; Ma, T.; Zhao, Y.G.; Xu, G.S. Energy requirements for maintenance and growth of Dorper crossbred ram lambs. *Livest. Sci.* **2012**, *150*, 102–110. [CrossRef]
47. Gomes, M.A.B.; Moraes, G.V.D.; Mataveli, M.; Macedo, F.D.A.F.D.; Carneiro, T.C.; Rossi, R.M. Performance and carcass characteristics of lambs fed on diets supplemented with glycerin from biodiesel production. *Rev. Bras. Zootec.* **2011**, *40*, 2211–2219. [CrossRef]
48. Shadnoush, G.; Ghorbani, G.; Edris, M. Effect of different energy levels in feed and slaughter weights on carcass and chemical composition of Lori-Bakhtiari ram lambs. *Small Rumin. Res.* **2004**, *51*, 243–249. [CrossRef]
49. Carpenter, Z.L. What is consumer-preferred lamb. *J. Anim. Sci.* **1996**, *25*, 1232–1235. [CrossRef]
50. Ray, E.E.; Mandigo, R.W. Genetic and environmental factors affecting carcass traits of lambs. *J. Anim. Sci.* **1966**, *25*, 449–453. [CrossRef]
51. Bradford, G.; Spurlock, G. Effects of castrating lambs on growth and body composition. *Anim. Prod.* **1964**, *6*, 291–299. [CrossRef]
52. Owens, F.N.; Dubeski, P.; Hanson, C.F. Factors that alter the growth and development of ruminants. *J. Anim. Sci.* **1993**, *71*, 3138–3150. [CrossRef] [PubMed]
53. Hamoen, J.R.; Vollebregt, H.M.; Van der Sman, R.G.M. Prediction of the time evolution of pH in meat. *Food. Chem.* **2013**, *141*, 2363–2372. [CrossRef]
54. Tarumán, J.A.; Smulders, J.P.; Gallo, C.B. Risk factors for bruises and high muscle pH in lamb carcasses of Tierra Del Fuego. Chilean Patagonia. *Open Access Library J.* **2018**, *5*, e4291. [CrossRef]
55. Watanabe, A.; Daly, C.C.; Devine, C.E. The effects of the ultimate pH of meat on tenderness changes during ageing. *Meat Sci.* **1996**, *42*, 67–78. [CrossRef] [PubMed]

56. Devine, C.E.; Graafhuis, A.E.; Muir, P.D.; Chrystall, B.B. The effect of growth rate and ultimate pH on meat quality of lambs. *Meat Sci.* **1993**, *35*, 63–77. [CrossRef]
57. Stewart, S.M.; McGilchrist, P.; Gardner, G.E.; Pethick, D.W. Association between loin ultimate pH and plasma indicators of pre-slaughter stressors in Australian lamb. *Meat Muscle Biol.* **2018**, *2*, 254–264. [CrossRef]
58. Gardner, G.E.; McGilchrist, P.; Pethick, D.W. Ruminant glycogen metabolism. *Anim. Prod. Sci.* **2014**, *54*, 1575–1583. [CrossRef]
59. Liu, Q.; Wang, C.; Yang, W.Z.; Guo, G.; Yang, X.M.; He, D.C.; Dong, K.H.; Huang, Y.X. 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*, 605–614. [CrossRef]
60. Zhang, X.Z.; Meng, Q.X.; Lu, L.; Cui, Z.L.; Ren, L.P. 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*, 100–106. [CrossRef]
61. Hopkins, D.L.; Hegarty, R.S.; Walker, P.J.; Pethick, D.W. Relationship between animal age, intramuscular fat, cooking loss, pH, shear force and eating quality of aged meat from sheep. *Aust. J. Exp. Agric.* **2006**, *46*, 879–884. [CrossRef]
62. Bernués, A.; Ripoll, G.; Panea, B. Consumer segmentation based on convenience orientation and attitudes towards quality attributes of lamb meat. *Food. Qual. Prefer.* **2012**, *26*, 211–220. [CrossRef]
63. Font-i-Furnols, M.; Guerrero, L. Consumer preference, behavior and perception about meat and meat products: An overview. *Meat Sci.* **2014**, *98*, 361–371. [CrossRef]
64. Neethling, N.E.; Suman, S.P.; Sigge, G.O.; Hoffman, L.C.; Hunt, M.C. Exogenous and endogenous factors influencing color of fresh meat from ungulates. *Meat Muscle Biol.* **2017**, *1*, 253–275. [CrossRef]
65. Prache, S.; Schreurs, N.; Guillier, L. Review: Factors affecting sheep carcass and meat quality attributes. *Animal* **2022**, *16*, 100330. [CrossRef]
66. Piao, M.; Jung, D.; Kang, H.J.; Park, S.J.; Lee, J.O.; Kim, M.; Kim, H.J.; Kim, D.H.; Seo, J.K.; Jo, C.; et al. Effects of dietary glycerol inclusion on growth performance, carcass and meat quality characteristics, glycogen content, and meat volatile compounds in Korean cattle steers. *Anim. Biosci.* **2021**, *34*, 603–612. [CrossRef] [PubMed]