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Article

Productive response, carcass traits, and meat quality of sheep fed with increasing levels of crushed dry fruits of *Acacia farnesiana*

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Abstract:

The present research evaluated the productive response, carcass traits, and meat quality of sheep fed with increasing levels of crushed dry fruits of *Acacia farnesiana* (CDFAf). Thirty-two sheep (20 ± 2.5 kg and age 70 ± 15 d) were used. Four levels of CDFAf (T0=0.0, T1=1.5, T2=3.0, and T3=4.5 %) were evaluated. The stages of growing (21 d) and finishing (49 d) were assessed. Initial and final live weight (ILW and FLW), dry matter intake (DMI), daily and total weight gain (DWG and TWG), and feed efficiency

(FE) were measured. On d 70, the animals were slaughtered to determine carcass traits (CaT), carcass morphometry (CaM), primal cut weight (PrCW), viscera weights (ViW), and meat quality parameters (MeQ). The addition of CDFAf did not affect the DMI; it positively affected DWG and TWG in the growing stage (P<0.05). No differences (P>0.05) were found in the productive variables during the finishing stage. The PrCWs differed (P<0.05), with T1 and T3 registering the highest weights in the loin and neck, respectively. The MeQ shows significant differences in the shear force and water retention capacity at 24 and 72 h. Better tenderness in the meat was observed in T1, and a greater loss of water and greater shear force was observed in T3. It is concluded that CDFAf improves weight gain and yield of primal cuts.

Keywords: Sheep, Safety, Meat quality, Huisache.

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Introduction

Currently, intensive sheep production systems are affected by the increase in the cost of inputs used in feeding, such as energy ingredients (corn and sorghum) and protein ingredients, such as soybeans and rapeseed[(1)], a situation that has an impact on the production costs of small-scale sheep systems[(2)]. Given this situation, it is necessary to incorporate nutritional strategies that reduce the use of external inputs, such as the use of local forage resources from trees[(3)] and leguminous shrubs, which have nutraceutical properties (protein and bioactive compounds) that, at low concentrations (50 g/kg of DM) in the diet, could improve the productive response of the animals. Forage plants that have a high concentration of condensed tannins, flavonoids, saponins, organosulfur compounds, and essential oils have the ability to favorably modify rumen fermentation by reducing the oxidation of amino acids[(4)], antimicrobial action on some intestinal microorganisms, improving intestinal health and consequently the absorption of nutrients, increasing propionic acid production[(5)], increasing food palatability, and stimulating intake by decreasing lipid oxidation[(6)]. In addition, these plants can continue to produce biomass under conditions of low soil moisture content[(5)]. *Acacia farnesiana* is a shrubby legume distributed in tropical and subtropical climates of Mexico, and one of its best adaptive agronomic benefits is that it is one of the first plants to appear in soils once they have been degraded by anthropogenic activities, giving rise to ecological succession to plants that are more demanding in nutrients[(7)]. This plant species represents a source of nutrients mainly of protein origin (up to 20 % of CP)[(8)] and high digestibility of organic matter[(7)]; its fruits are rich in secondary metabolites (condensed tannins, flavonoids, and polyphenolic compounds), chemical compounds that benefit animal health by improving its productive performance and meat quality[(8-13)]. Likewise, it has been reported that some

secondary metabolites present in *A. farnesiana*, such as flavonoids and tannins, contain antimicrobial, anti-inflammatory, antioxidant, and anthelmintic properties[11-16]. There is evidence that adding inclusion levels of up to 12 % of *A. farnesiana* dry fruits in diets (dry basis) for sheep does not affect production parameters[7]. For this reason, the present research aimed to evaluate the inclusion of increasing levels based on the amount of an organic fraction (EtOAc-F) present in crushed dry fruits of *A. farnesiana* in sheep feed during the growing and finishing stages in pen on the production parameters, carcass traits, primal cuts, carcass quality, and changes in viscera weight.

Material and methods

Experimental site

The study was conducted out at the Metabolic Unit of the UAEM-Temascaltepec University Center, located at 19º 2′ 40″ N and -100º 2′ 42″ W, at 1,800 m asl, in Temascaltepec de González, State of Mexico, Mexico. With rains in summer and an average annual temperature of 18 °C[17].

Plant material

Ripe fruits of *A. farnesiana* were collected in seven different localities (7 shrubs per site) in the municipality of Tejupilco (latitude 18°90′ 58″ N and longitude -100°15′27″ W) in the southwestern area of the State of Mexico, Mexico, during the spring. The fruits were collected between 0600 and 0700 h and transferred to the Animal Nutrition Laboratory of the UAEM-Temascaltepec University Center, where they were dried in the shade until they reached a constant weight and then ground in a hammermill (New Holland, 2315) to a particle size of 5 mm. This research group[14,15] previously reported the anthelmintic activity and identification of the main secondary metabolites of the plant material used in the present study.

Animals and feed

Thirty-two (32) crossbred male sheep (Katahdin x Charollais; LW 20 ± 2.5 kg and age 70 ± 15 d) were used; upon arrival at the Metabolic Unit of the UAEM-Temascaltepec University Center, they were weighed to group them according to their weight from highest to lowest and form eight homogeneous blocks of four animals each. Each animal was housed in an individual pen (0.8 x 1 m), which was equipped with a feeder and drinker. In each block, treatments were randomly assigned. After this, the sheep received intramuscularly one milliliter of ADE vitamin complex (Vigantol ®), equivalent to 250,000 IU of vitamin A, 37,500 IU of vitamin D3, and 25 mg of vitamin E, and 2.5 ml of 8-way bacterin (BOBACT 8 ®) for the prevention of clostridial diseases and pneumonia.

All animals received experimental diets (Table 1) for the growing stage (15 % CP and 2.9 Mcal/kg) and another for the finishing stage (14 % CP and 3.0 Mcal/kg), according to their nutritional requirements[18]. Both diets underwent proximate chemical analysis[19] and fiber fractionation[20] (Table 2). The diet was administered at three frequencies: 0700, 1300, and 1900 h, under the following proportions: 30, 30, and 40 %. All animals were fed throughout the experiment, considering their voluntary consumption, and they received clean and fresh water at will.

Table 1: Experimental diets for growing and finishing sheep added with different levels of crushed dry fruits of *Acacia farnesiana*

Ingredients (%)	Growing				Finishing			
	¥Control	T1	T2	T3	¥Control	T1	T2	T3
Rolled corn	37.8	37.1	36.3	35.3	50.0	50.0	50.0	50.0
Soybean meal	9.0	9.0	9.0	9.0	7.0	7.0	7.0	7.0
Rapeseed meal	6.0	6.0	6.0	6.0	7.5	7.5	7.5	7.5
Whole sorghum	9.0	9.0	9.0	9.0	9.3	8.5	7.5	6.5
CDFAf[Ψ]	0.0	1.5	3.0	4.5	0.0	1.5	3.0	4.5
Molasses	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0
Urea	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Alfalfa hay	22.5	21.7	21	20.5	10.0	9.3	8.8	8.3
Corn stover	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0
Mineral premix	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
Calcium carbonate					0.5	0.5	0.5	0.5
Common salt	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2

[¥] Treatments: Control: 0.0, T1: 1.5, T2: 3.0, and T3: 4.5 as % inclusion (BD) of the diet, [Ψ]CDFAf, crushed dry fruits of *Acacia farnesiana*.

Table 2: Chemical composition (%) of experimental diets and crushed dry fruits of *Acacia farnesiana*

Nutrient (%)	Growing				Finishing				*A. farnesiana*
	¥Control	T1	T2	T3	¥Control	T1	T2	T3	
DM	91.89	91.99	91.95	91.84	91.65	91.39	91.64	91.03	87.54
CP	15.17	15.45	15.35	15.06	14.32	14.04	14.12	14.08	12.52
EE	3.81	3.85	3.38	3.96	4.06	4.36	4.14	4.04	3.27
NDF	25.08	29.31	33.06	34.62	19.12	20.08	20.46	22.37	38.80
ADF	21.25	24.86	26.67	28.76	16.31	17.43	16.87	18.46	34.22
OM	89.80	90.20	90.05	90.20	91.10	91.40	91.10	90.60	91.30
Minerals	10.20	9.80	9.95	9.80	8.90	8.60	8.90	9.40	8.70

[¥] Treatments: Control: 0.0, T1: 1.5, T2: 3.0, and T3: 4.5 as % inclusion (BD) of the diet; DM= dry matter, CP= crude protein, EE= ethereal extract, NDF= neutral detergent fiber, ADF= acid detergent fiber; OM= organic matter.

Experimental test

The feeding test lasted 80 d, of which 10 were for adaptation to the pen and diets, and there were two experimental periods: growing stage for 21 d and finishing stage for 49 d of feeding. The treatments were different levels of crushed dry fruits of *A. farnesiana* (CDFAf): Control: 0, T1: 1.5, T2: 3.0, and T3: 4.5 %, of the basal diet (BD) both in the growing stage and the finishing stage. For the inclusion levels of CDFAf, they were based considering the bioactive compounds of an organic fraction (EtOAc-F), using the same batch of pods as those of the present study. The specific chemical compounds within this fraction were: gallic acid, ethyl gallate, naringin, and naringenin[15]. The yield of EtOAc-F was 3.75 %, which was equivalent to 562, 1,125 and 1,687 mg of EtOAc-F in T1, T2, and T3, respectively.

Evaluation of the productive response

After the 10 d of adaptation to the individual pens and feeding, the animals were weighed for three consecutive days (with prior fasting) to know the initial live weight (ILW), then they were weighed on d 21 (growing phase) and d 70 (finishing period). Dry matter intake, total weight gain, daily weight gain, feed conversion, and feed efficiency were recorded throughout the experimental phase.

Post mortem variables

On d 70 of the experimental period, the animals were transferred to a private slaughterhouse in the municipality of Capulhuac, State of Mexico, to be slaughtered according to NOM-033-SAG/ZOO-2014 and Colomer-Rocher *et al*[21]. The live weight (LW) of the animals when leaving the farm and arriving at the slaughterhouse was recorded to estimate the farm yield (farm yield, %= (LW arrival at the slaughterhouse, kg/LW exit of the farm, kg)*100. Twelve (12) hours after arrival at the slaughterhouse, the LW was previously recorded to determine the commercial yield (%)= (hot carcass, kg/LW at slaughter, kg)*100.

Viscera and byproducts

Once the animal was slaughtered, the weights of blood, skin, head and legs, red viscera (heart, liver, lungs, and trachea) and empty green viscera (rumen, reticulum, omasum and abomasum, and large and small intestines) were recorded. The weight of some organs of the reproductive system (testicles and penis) and the weight of the total internal fat of the thoracic and abdominal cavities were also recorded.

Carcass traits and quality

At 45 min *post mortem*, the weight of the hot carcass (portable digital scale, Rhino), pH and temperature (Hanna potentiometer) of the *Longissimus thoracis* muscle between the 12th and 13th ribs were recorded[22]. The carcass was then taken to the cold chamber (4 °C) and at 24 h, the weight of the cold carcass, pH, and temperature were recorded. The color of the *Pectoralis profundus* muscle and the color of the superficial fat of the *Gluteus medius* muscle were measured; this variable was evaluated by the L* (lightness), a* (reddish), and b* (yellowish) system[23] with a Minolta colorimeter (Chroma Metro CR-200, Minolta Camara C., Osaka, Japan)[22]. GR grades were also measured, which indicate the total depth of tissue (mm) between the carcass surface and the rib, over the 12th rib region and at a point 11 cm from the midline; this indicator estimates subcutaneous fat: little or no fat cover (GR 0 to 4 mm), moderate fat cover (GR to 9 mm), abundant fat cover (GR 10 to 15 mm), excessive fat cover (GR >15 mm)[24]. Between the 12th and 13th rib, the area of *Longissimus thoracis* muscle was determined; the area under the rib was measured in the 12th rib by using a plastic grid or by tracing the eye on acetate paper and then using a grid (GRID-USDA) to determine the area in centimeters[25].

Morphometric characteristics and primal carcass cuts

Cañeque *et al*[22] and Colomer-Rocher *et al*[21] methodologies were used to measure carcass length, rump perimeter, leg length and circumference (tape measure), and the greatest and smallest width of the thorax (metric compass). The entire carcass was divided to record weight (Torrey digital scale with an accuracy of 0.05 g) of commercial parts: legs, neck, shoulder, rack, ribs, and loin[26].

Water loss, shear force, and meat color

For the meat quality analysis, 350 g of meat was taken from the *Longissimus thoracis* muscle from the 6th to 3rd rib of the cold carcass. The sample was deposited in a cooler to be transported to the meat quality laboratory of the UAEM-Temascaltepec University Center, which was used to determine the variables: drip water loss, shear force, and meat color (24, 48, and 72 h). Honikel's[27] technique was used to determine drip water loss. Two fat-free samples of 50 g each with a thickness of 1.5 cm were taken. Each sample was hooked and placed in an airtight bag, so that the meat was suspended inside the bag. In this way, all samples were hung inside a refrigerator at 4 °C. Weights were recorded at 24, 48, and 72 h later (analytical scale, Ohaus ± 0.05 g). Drip water loss was calculated using the following formula:

$$Drip\ water\ loss\ (\%) = \frac{Sample\ final\ weight\ (g)}{Sample\ initial\ weight\ (g)}\ X\ 100$$

In meat shear force, Bratzler's[28] methodology was used. Samples 4 cm long x 4 cm wide and 2.5 cm thick; these samples were previously vacuum packed and refrigerated at 4 °C for 3 d in order to reach 80 % softening. After that period, the samples were unpacked and placed in a plastic bag, sealed, and cooked in a double boiler (70-75 °C) for an hour and a half; at the end, the internal temperature was recorded, they were left to cool (30 min in clean water), and the shear force (kg) parallel to the muscle fibers was determined with the help of a texture meter (TAXT2, Stable Microsystems Corp, NY, USA) equipped with WarnerBrazler shear blades at a speed of 50 mm/min.

Meat color was determined with a Minolta CR-20 colorimeter, Konica Minolta, Osaka, Japan, using the CIE methodology[29]. It measures the color with the Hunter system: high values of L* are associated with pale colors: 0 (black), 100 (white); a*, high values determine a higher intensity of red: a*>0 (red), a*<0 (green); b*, high values are associated with a more yellowish tone of the meat: b*>0 (yellow), b*<0 (blue). These measurements were made during the 24 h *post mortem* using a sample of 4 x 4 cm with a thickness of 2.5 cm. The same sample was refrigerated at 4 °C for the determinations at 48 and 72 h. Readings were taken at three sample sites free of excess intramuscular fat and blood spots.

Experimental design and analysis of results

The results obtained were subjected to an analysis of variance using the GLM procedure of SAS[30] under a randomized complete block design, taking the animals' initial live weight (ILW) as a blocking factor, which was used as a covariate in the statistical analyses. The comparison of means between treatments was determined with Tukey's test; significant differences were declared when $P \leq 0.05$ and trends when $0.05 < P \leq 0.1$.

Results

Productive response

Dry matter intake was not affected ($P \geq 0.05$) by the addition of the different levels of crushed dry fruits of *A. farnesiana* (CDFAf) in both evaluation periods. During the growing period of the animals, CDFAf increased ($P \leq 0.05$) DWG, TWG, and FLW, while FE tended ($P=0.1$) to improve (Table 3). During the finishing stage, no significant differences or trends ($P>0.1$) were found between treatments.

Table 3: Productive behavior of sheep during the growing and finishing stages receiving different levels of crushed dry fruits of *Acacia farnesiana*

Stage/Variable		Treatments				SEM	*P*-value
		Control	T1	T2	T3		
Growing	ILW, kg	22.87	22.94	22.79	22.76		
	FLW, kg	28.36[b]	29.95[ab]	29.83[ab]	30.43[a]	0.44	0.02
	DMI, kg/d	1.50	1.53	1.49	1.62	0.17	0.45
	DWG, kg/d	0.26[b]	0.33[ab]	0.33[ab]	0.36[a]	0.05	0.02
	TWG, kg	5.52[b]	7.10[ab]	6.99[ab]	7.59[a]	1.25	0.02
	FE, kg	0.17[b]	0.22[a]	0.22[a]	0.22[a]	0.04	0.10
Finishing	ILW, kg	28.05	29.28	29.65	30.91		
	FLW, kg	45.69	45.70	46.88	46.23	2.79	0.81
	DMI, kg/d	1.52	1.50	1.50	1.63	0.17	0.52
	DWG, kg/d	0.33	0.33	0.35	0.34	0.05	0.82
	TWG, kg	16.29	16.28	17.45	16.82	2.78	0.82
	FE, kg	0.21	0.21	0.23	0.21	0.30	0.06

[¥] Treatments: Control: 0.0, T1: 1.5, T2: 3.0, and T3: 4.5 as % inclusion (BD) of the diet, ILW= initial live weight, FLW= final live weight, DMI= dry matter intake, DWG= daily weight gain, TWG= total weight gain, FE= feed efficiency. SEM= standard error of the mean.

[ab] Different literal in the same row indicates differences ($P \leq 0.05$).

Carcass traits, primal cuts, and viscera weight

Carcass traits (Table 4) and morphometry (Table 5) were not affected ($P > 0.05$) by the addition of CDFAf. In the commercial primal cuts (Table 6), T3 tended to improve ($P = 0.09$) neck weight. The addition of CDFAf at the 1.5 % level improved ($P \leq 0.01$) the weight of the loin. No significant differences ($P > 0.05$) were found in the non-meat components between the treatments evaluated.

Table 4: Carcass traits of sheep finished in pens added with different levels of crushed dry fruits of *Acacia farnesiana*

Variable	Treatments				SEM	*P*-value
	¥Control	T1	T2	T3		
FY, %	46.63	48.35	48.37	48.50	2.03	0.24
CY, %	50.93	52.70	52.87	52.81	1.95	0.17
L* carcass	38.72	39.22	40.17	41.52	2.90	0.26
a* carcass	10.45	12.43	10.42	10.20	2.03	0.13
b* carcass	8.15	9.94	6.02	7.24	2.90	0.09
L* fat	70.92	69.62	69.62	70.65	3.05	0.75
a* fat	1.72	1.68	2.18	2.20	0.82	0.45
b* fat	10.39	10.67	10.97	11.03	1.25	0.73
pH45	6.61	6.62	6.60	6.49	0.17	0.44
pH24	5.83	5.66	5.65	5.80	0.21	0.26
T°45	28.34	29.18	28.82	29.60	1.48	0.39
T°24	1.72	2.43	2.06	2.31	1.03	0.54
Back fat, mm	2.43	2.79	3.26	2.92	0.88	0.34
GR Grades	10.94	12.06	12.75	12.48	2.89	0.62
RiEA, cm^2	21.9	23.7	23.0	22.7	2.71	0.64

¥ Treatments: Control: 0.0, T1: 1.5, T2: 3.0, T3: 4.5 as % inclusion (BD) of the diet, FY= farm yield, CY= commercial yield, RiEA= rib eye area.

Table 5: Morphometry of carcasses of sheep finished in pens added with different levels of crushed dry fruits of *Acacia farnesiana*

Variables	Treatments				SEM	*P*-value
	¥Control	T1	T2	T3		
HCW, kg	21.75	23.11	23.29	23.29	1.65	0.22
CCW, kg	21.19	22.44	22.65	22.61	1.67	0.27
CL, cm	66.27	65.07	66.52	66.69	2.01	0.39
LL, cm	35.56	34.58	36.23	34.89	1.81	0.30
LD, cm	41.14	41.49	43.33	42.33	1.97	0.16
RP, cm	61.62	62.18	63.18	59.49	5.12	0.54
RW, cm	21.34	22.05	21.85	22.00	1.04	0.52
LWT, cm	23.47	24.45	23.59	24.51	1.73	0.50
SWT, cm	19.23	19.67	19.54	19.53	0.91	0.80

¥ Treatments: Control: 0.0, T1: 1.5, T2: 3.0, and T3: 4.5 as % inclusion (BD) of the diet. SEM= standard error of the mean. HCW= hot carcass weight, CCW= cold carcass weight, CL= carcass length, LL= leg length, LD= leg diameter, RP= rump perimeter, RW= rump width, LWT= largest width of the thorax, and SWT= smallest width of the thorax.

Table 6: Weight of primal cuts (kg) of sheep added with different levels of crushed dry fruits of *Acacia farnesiana*

Variable (kg)	Treatments				SEM	*P*-value
	¥Control	T1	T2	T3		
Legs	6.74	7.09	6.65	7.18	1 .14	0.75
Neck	1.01 [b]	0.98 [b]	1.02[b]	1.3[a]	0.18	0.09
Shoulder	6.07	6.44	7.01	6.91	1.24	0.43
Rack	1.98	2.11	2.12	2.12	0.33	0.82
Ribs	3.51	3.34	3.29	3.26	0.50	0.75
Loin	1.88[b]	2.32[a]	2.17[ab]	2.16[ab]	0.25	0.01

¥ Treatments: Control: 0.0, T1: 1.5, T2: 3.0, T3: 4.5 as % inclusion (BD) of the diet. SEM= standard error of the mean.

[ab] Different literal in the same row indicates statistical differences ($P \leq 0.05$).

Meat quality

In the meat quality variables (Table 7), differences ($P<0.05$) were observed on drip water loss at 24 and 72 h, with T1 having the lowest water loss with 6.76 %, while T2 presented the highest runoff with 8.99 % at 72 h. The shear force also showed significant differences ($P<0.05$), where the control group obtained a lower shear force compared to the other treatments.

Table 7: Quality parameters of meat from sheep finished in pens added with different levels of crushed dry fruits of *Acacia farnesiana*

Variable/Treat	Hour	Treatments				SEM	*P*-value
		¥Control	T1	T2	T3		
L* meat		29.45	28.93	28.29	28.00	2.42	0.64
a* meat	H0	8.45	8.03	8.29	7.68	1.20	0.60
b* meat		9.04	8.70	8.80	8.36	1.19	0.72
L* meat		33.22	32.69	32.6	31.134	2.87	0.51
a* meat	H24	8.35	9.06	9.13	8.80	1.59	0.75
b* meat		10.90	11.10	10.20	9.80	2.38	0.67
L* meat		32.83	32.96	32.45	32.15	2.35	0.90
a* meat	H48	9.61	10.26	10.67	10.31	1.27	0.42
b* meat		11.27	11.59	12.17	11.71	1.54	0.71
L* meat		32.03	32.30	30.93	31.33	1.88	0.48
a* meat	H72	9.61	10.26	10.67	10.31	1.01	0.13
b* meat		12.56	12.49	13.17	12.36	1.38	0.66
DWL (%)	H24	2.19[ab]	2.34[ab]	3.28[a]	1.75[b]	0.911	0.02
	H48	4.71	4.39	5.55	3.88	1.38	0.14
	H72	7.95[ab]	6.76[b]	8.99[a]	7.61[ab]	1.19	0.01
SF (kg)		3.07[b]	3.60[ab]	4.79[a]	3.74[ab]	0.93	0.01

¥ Treatments: Control: 0.0, T1: 1.5, T2: 3.0, T3: 4.5 as % inclusion (BD) of the diet. SEM= standard error of the mean, DWL= drip water loss, SF= shear force.
ab Different literal in the same row indicates statistical differences ($P \leq 0.05$).

Discussion

Productive behavior

Dry matter intake (DMI). The DMI is one of the most critical parameters when using ingredients rich in phenolic compounds (condensed tannins, hydrolyzable tannins, and flavonoids) as part of the animals' diet. Previous studies carried out by this research group on the same CDFAf samples found that they contain phenolic compounds, such as ethyl gallate, methyl gallate, gallic acid, naringin, and naringenin[14,15]. These compounds could be interacting in the metabolism of dietary nutrients and modifying the productive response of animals; this coincides with other studies that have reported that the total phenols of *A. farnesiana* fruits may be around 397.5 g/kg of dry matter[31]. In general, phenolic compounds have different bioactive effects when consumed by animals, for example, flavonoids, such as naringin and naringenin that were found in the same dried pods of *A. farnesiana* that were used in the present study and those of previous studies[14,15], could increase the digestion of structural carbohydrates (cellulose and hemicellulose) of the plant cell walls, and they could also modify microbial protein synthesis, favoring cellulolytic species and inhibiting methanogenic protein[32]. Biologically, this can be explained by the fact that phenolic compounds, such as flavonoids and condensed tannins, due to their molecular weight, can form complexes with dietary proteins and carbohydrates through four chemical reactions: a) hydrogen bonds between the hydroxyl radicals of the phenolic groups and the oxygen of the amide groups of the peptide bonds of the proteins, which can be reversible depending on the pH of the medium, b) hydrophobic interactions between the aromatic ring of the phenolic compounds and the hydrophobic regions of the protein, c) ionic bonds between the phenolate ion of gallic acid and the cationic site of the protein; this type of complexes are exclusive to hydrolyzable tannins and are reversible[33]. The gallic acid found in CDFAf is part of the chemical structure of hydrolyzable tannins and could form complexes with dietary proteins, modifying the site of digestion and absorption of nutrients, and finally, d) when polyphenols oxidize to quinones, they can form complexes with dietary proteins through covalent bonds; this type of complex is reversible[33]. Considering that the highest inclusion level of CDFAf in the present study was 45 g/kg DM and 39.7 % of that amount is total phenols, it is estimated that the diet only had 17.86 g of bioactive compounds, a concentration that could have a synergistic effect with the metabolism of dietary nutrients. Additionally, in the present study, the addition of CDFAf did not show differences between treatments for dry matter consumption in both production stages (Table 2), which could be related to the levels of inclusion in the diet of the bioactive compounds that were used, as they were below 50 g/kg DM, a concentration that has been considered beneficial as it does not have a negative effect on the voluntary consumption of animals. Intakes greater than this amount can negatively affect dry matter intake and,

consequently, the productive response of animals[33]. Other studies have also reported no negative effect of including *A. farnesiana* in the diet when 120 to 240 g/kg of DM were used; on the contrary, when the inclusion was 300 g/kg of DM, consumption in sheep was increased[7,34]. It is important to consider that, in this type of study, the specific bioactive compounds found in the DM of plants must be determined because the biological response in animals will depend on the chemical nature and concentration of each of them. In this sense, Quiroz-Cardoso *et al*[9] mention that the condensed tannins in fruits of *A. farnesiana* do not influence consumption or palatability index, but the amount of total phenols does affect this parameter. The concentration of secondary compounds in *A. farnesiana* can be variable and depends on the state of maturity of the fruits, the soil and environmental conditions in which they develop, and the morphological and chemical nature of the type of compound[9,10,35]. Therefore, for future research, the state of ripeness of the fruits and the quantification of specific bioactive compounds should be considered.

Weight gain. Both daily weight gain (DWG) and total weight gain (TWG) in the growing stage were positively affected by treatments that included CDFAf, which were reflected in the final live weight (FLW) of the animals. The DWG found in this study was 260, 330, 330, and 360 g/d for the growing period and 330, 330, 350, and 340 g/d in the finishing stage for the control, T1, T2, and T3, respectively. The increase in production variables during the growing stage could be attributed to the fact that the animals consumed a diet higher in protein, and if it is considered that the phenolic compounds (ethyl gallate, methyl gallate, gallic acid, naringin, and naringenin) present in CDFAf are chemical compounds of high molecular weight[4] and complex chemical structure with a large number of hydroxyl groups, which can form complexes[36] with the amino acid proteins and reserve and structural polysaccharides of the diet[6], which at neutral pH are insoluble, which, when passed to the abomasum, dissociate due to the effect of acidic pH[37-38], increasing the pool of metabolizable protein to the duodenum, thus increasing the availability of amino acids for muscle protein synthesis, which translates into greater weight gain, as happened in the animals that received CDFAf in the present research.

Another mechanism may be the alteration that they generate on the bacterial populations of the rumen since they can inhibit the growth of protozoa and fibrolytic bacteria, and in turn, stimulate the proliferation of amylolytic bacteria such as *Succinimonas amylolytica* and *Selenomonas ruminantium*, which produce propionate[39]. Likewise, adding saponins from some species improves the efficiency of microbial protein synthesis, leading to a more energy-efficient fermentation process[39]. In this context, future studies on rumen fermentation parameters, bacteria count, and secondary metabolites in rumen will be considered. In many tropical and subtropical regions of Mexico and the world, there are various trees and shrubs rich in these bioactive compounds, which could be used as a nutraceutical strategy to improve animal productivity in rural areas of the world where the use of concentrated protein or energy feeds is not widely available. There are other studies that have included tree and shrub forages in animal feed; specifically, when *Guazuma ulmifolia*[40] was included, there was an improvement in weight gain; the same

happened in García-Winder *et al*'s[7] research when including 12 % of *A. farnesiana* fruits in the diet of growing Pelibuey ewe lambs.

Carcass traits, primal cuts, and viscera weight

Carcass quality is one of the most important parameters to evaluate in sheep production and marketing processes because it largely determines the selling price.

Carcass color. In the present study, the color of the carcass was similar to that reported by Jaborek *et al*[41] for L* with 40.91; in this sense, L* values are affected by myoglobin concentration, which varies with the age of the animals[41]; in contrast, the values of a* and b* differ from those reported by Jaborek *et al*[41]. This variation in the results found in this study and previous studies is possibly due to the age of the animals and the type of diet[26].

Fat color. The color of the fat in this study did not show significant differences between treatments compared to the control; the values found for L* coincide with those reported in other studies[41], while the values of a* of the same authors (8.63) were higher than those found in this study, an effect attributed to the type and level of energy in the diet and age and sex of the animals evaluated; however, they also mention that handling during slaughter can be important. Regarding the values of b*, those found in the present study were slightly higher than those found by Jaborek *et al*[41]; this yellowish color could be attributed to the carotenoids and xanthophylls commonly present in all green forages, which cause yellowing in fat; these compounds could be present in the CDFAf that were used in the present study.

PH. The carcass pH values (5.65-5.83) obtained in this study at 24 h for all treatments were similar to those reported by other studies[41] for sheep from the Dorset x Hampshire cross. In contrast, they were slightly higher than those observed by Partida de la Peña *et al*[24], who reported average pH values of 5.5 at 24 h after slaughter. The variation in this parameter depends on different factors, such as the handling of the animals at the time of slaughter and the age of the animals[42-44]. Similarly, some authors have reported variation due to the type of diet since carcasses from animals finished with high-grain diets may present higher values compared to animals whose diet was based on forage[41].

Back fat. The fat cover in the carcass is the main factor that determines its commercial value since it prevents the carcass from drying out, influences the tenderness and juiciness of the meat, and, in the case of sheep, interferes with the aroma and flavor of the meat[26]. The back fat obtained in this experiment was low (2.43, 2.79, 3.26, and 2.92 mm, respectively) compared to what was reported in another study[45], where they obtained 6.33 mm. This characteristic is due to the exit weight of the animals, which indicates that the slaughter weights can be increased[45]. In this sense, the Mexican standard for the classification of carcasses allows up to 6.9 mm of subcutaneous fat cover in heavy lambs to be considered in the "MEX EXT" classification.

GR Grades. The thickness of the dorsal subcutaneous fat is an objective parameter highly correlated with most of the tissue of the carcass, mainly the three pieces of the highest commercial value[26]. In this sense, the measurements of the GR point are another alternative related to the amount of fat in the entire carcass, which facilitates its implementation without interfering with the slaughter line of the animals[46]. In this study, no differences (P>0.05) were found for this variable due to the effect of the treatments (10.94, 12.06, 12.75, and 12.48) for T0, T1, T2, and T3, respectively; these results are within the ranges proposed by Bianchi[47] for carcasses weighing 18.5 to 22 kg.

Rib eye area. The *Longissimus dorsi* muscle is an important variable in determining carcass quality since it is highly correlated with the total amount of muscle in the carcass and corresponds to the rack and loin, which are the pieces with the highest economic value[45]. In this study, although no differences were found (P>0.05), there was an increase in the treatments compared to the control (Table 4). Likewise, the values found in the present study for this parameter are higher than those reported in a study with Katahdin sheep (17.4 cm^2) and the average data reported by Partida de la Peña *et al*[24] for intensively finished sheep, which is due to the genotype of the animals studied.

Carcass yields. The yields found in this study are largely consistent with Partida de la Peña *et al*[24], who reported an average of 50.9 % of carcass yields for sheep finished in intensive systems, which coincides with what was found in this study for T0; the yields of T1, T2, and T3 were higher than those reported by these authors.

Primal cuts. The yield of primal cuts is an important factor for the marketing of sheep meat when it comes to cuts since each of them receives a different value. In this study, the weights of the primal cuts were similar (P>0.05) for legs, neck, shoulder, rack, and ribs (Table 6), which coincides with what was reported in Pelibuey sheep fed with waste chickpeas[48] and in hair sheep fed with different proportions of *Tithonia diversifolia*[49]. Nonetheless, statistical differences were observed in the weight of the loin (P<0.05) (Table 6). The weight and yield of primal cuts are associated with the slaughter weight and the feeding system[49].

Morphometry. The measurements corresponding to this item agree with what has been reported by other authors[45] for carcasses from the Katahdin-Charollais cross and with Partida de la Peña *et al*[24] in carcasses from intensively finished sheep. In this sense, these variables were not affected by the levels of inclusion of *A. farnesiana* pods since these depend to a large extent on the breed and age of the animals[24].

Viscera. It is believed that the workload of absorption, rather than the amount or characteristics of the digestion in the small intestine, has a significant impact on the intestinal mass, just as the weight, texture, or chemical composition of the digestion affects the mass of the gastrointestinal tract[50]. In this study, the weight of the different components of the digestive tract was not affected, which is consistent with various studies that included supplementation with legume fruits[42,51]. The weight of the different

organs (heart, liver, lungs) was not affected by the inclusion of *A. farnesiana* fruit meal, which indicates that it is a suitable supplement for animal consumption. The weight of total fat was high due to the use of isoenergetic and isoprotein diets, which resulted in the accumulation of fat in the kidneys and pericardium[52].

Meat quality

Flesh color. In this study, no significant differences (P>0.05) were observed in the values of L*, a*, and b* for treatments containing *A. farnesiana* fruits. Nevertheless, the L* color values were lower than those reported by Smeti *et al*[53], a* values were below the standards mentioned by Alberti *et al*[54], and b* values were within the standards[29] of the UNE 48-103-94 standards, where they indicate the thresholds of the color of pink flesh L* 44.0-51.6, a* 11.6-15.1, b* 9.8-17.6, and DFD (dark – firm – dry) meat L*25.1-32.8, a* 17.0-21.3, b* 7.2-16.9. These color changes after cutting (hour 0) will vary when they come into contact with oxygen and reach their maximum values after 48 h[54]. Other authors point out that the acceptable standard for the color of lamb meat is equivalent to a L*value 34-35 and a* value < 19; these color thresholds indicate that lamb meat with an L chromatic value between 34 and 35 (showing lightness) and a redness value (a) below 19 (indicating less redness) would be acceptable[55]. However, these criteria may differ according to the rating of regional standards and consumer preferences[56,57]. This performance coincides with that reported by Luciano *et al*[58] for b*; although the pH of the meat was not recorded, the pH of the carcass at 24 h was >5.6, possibly due to the stress of transport and *pre mortem* handling of the sheep, which affected the pH and DFD meat as a consequence[59]. On the other hand, other authors[53] reported a similar behavior for a* values on the ninth day of maturation. With storage time, b* values correlate positively with sensory appreciation of meat degradation, while a* correlates negatively with sensory color degradation[58]. These color changes in meat can be affected by the oxidative processes of myoglobin in contact with oxygen (the amount of myoglobin in the muscle determines the color saturation: purple-red myoglobin, bright red oxymyoglobin, brown metmyoglobin)[60]. The color of the fat will be the deposit of pigments from the food (xanthophylls, carotenes, etc.)[54].

Drip water loss. According to the results obtained in the present research, the lowest level of CDFAf inclusion presented the lowest values of drip water loss (hour 72) if it is considered that the water in meat can be found bound, immobilized, and free and the distribution of its electrons is not neutral but has a positive and a negative charged end, which means that they can be associated with reactive groups of various chemical compounds, such as proteins and phenolic compounds of *A. farnesiana*, due to their complex chemical structure and the large number of free hydroxyl groups, they can form complexes with water at the tissue level and increase the water retention capacity of the muscle[36].

Shear force. Texture is a variety of sensations related to chewing, cutting, and penetration of meat and is the parameter most respected by consumers[61]. The differences found in

this study show a tendency to increase the shear force as the levels of inclusion of *A. farnesiana* fruits increased. As the shear force in the treatments where CDFAf was included increased, it can be hypothesized that intramuscular fat decreased since this gives tenderness to the meat; these findings are good from the point of view of lean meats. It is considered that one of the most critical factors influencing meat quality is the oxidative process, which is decreased when the meat has less fat, increasing shelf life, which has been reported to be possible by including antioxidant phytochemicals in the animals' diet[62]. Other studies support this scientific justification by mentioning that phenolic compounds in the diet have been proposed to be effective in improving the antioxidant status of meat, contributing to the stabilization of color and flavor, and preventing rancidity[6,63].

Conclusions and implications

According to the results obtained in this study, CDFAf can be included in diets for growing and finishing sheep because no adverse effect was found on dry matter intake; it can improve weight gain in the growing stage and increase the weight of cuts of high commercial value, such as loin. The use of the fruits of this shrub species represents a potential option as a feed to improve ruminant production and reduce the use of feed inputs external to the production unit.

Conflict of interest

The authors of this paper declare that there is no conflict of interest.

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