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Ruminant Nutrition

Intake, growth performance, carcass traits, and meat quality of feedlot lambs fed novel anthocyanin-rich corn cobs

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ABSTRACT

Feeding anthocyanin- and antioxidant-rich forages to sheep and dairy cows can improve performance and product quality. The objective of this study was to evaluate the impact of feeding anthocyanin-rich (Hi-A) corn cobs on the growth performance and meat quality of lambs. A total of 30 eight-month-old Rambouillet ewe lambs (body weight 30.7 ± 1.2 kg) were fed for 63 days with three diets consisting of 80% concentrate and 20% roughage: Hi-A corn cobs (Hi-A), regular corn cobs (Low-A), and bermudagrass hay (BGH). A completely randomized design trial with 10 lambs per treatment was used. Data were collected on dry matter intake (DMI), body weight (BW), average daily gain (ADG), gain:feed ratio (G:F), carcass traits, meat color, fatty acid (FA) profile, volatile aroma compounds, and sensory panels. After feeding for 63 days, lambs were harvested, and the carcasses were evaluated. Boneless lamb loin chops were fabricated and submitted to FA, aroma, and sensory analysis. The corn cob diets did not affect BW, ADG, or G:F of the lambs compared to BGH diet, but DMI ($P < 0.01$) was decreased. The dressing percentage was greater ($P < 0.05$) in lambs fed BGH than in those fed Hi-A, while lambs fed Low-A did not differ from the other two diets. Loin chop instrumental color characteristics were not influenced by diets, except the hue angle, which was greater ($P < 0.05$) in lambs fed Hi-A than Low-A, while BGH did not differ from lambs fed either cob diet. There was no significant difference in the meat fatty acid profile. Five volatile compounds were affected by diets. The 2-butanone ($P = 0.07$) and 2,3-butanedione ($P = 0.05$) were greater in chops from lambs fed BGH relative to lambs fed Hi-A and neither differed ($P > 0.05$) from lambs fed Low-A diet. The 2-propanone was greater ($P = 0.01$) in chops from lambs fed BGH than in those fed either the Low-A or Hi-A diets. Both 3-methyl-butanal and methyl benzene were lower ($P = 0.01$ and $P = 0.02$, respectively) in chops from lambs fed the Hi-A diet than in those fed either the BGH or Low-A diet. Replacing 20% bermudagrass hay with corn cobs in the diets of feedlot lambs did not affect sheep growth performance, meat fatty acid profile, sensory traits, and most carcass characteristics and meat color parameters. Hi-A corn diet improved aroma in cooked boneless loin chops, but sensory traits were not affected. This study showed the Hi-A corn cobs can be safely used for roughage and feed for lambs and for improving meat aroma in cooked boneless loin chops.

Key words: anthocyanin-rich corn, aroma, feed, lamb, meat quality

INTRODUCTION

Corn cobs are crop residues that have been used as non-forage fiber sources for feeding large (Matsushima et al., 1957) and small (Bell, 1949) ruminants. However, in most situations, corn cobs are returned to the field with the corn stover after grain harvest (Varvel and Wilhelm, 2008). Corn residue is an abundant and inexpensive source of biomass that can be removed from fields without deleterious production or environmental effects if proper management is used. Considering that U.S. corn production was 383.5 million Mg in 2021 (USDA, 2022), there were approximately 69 million Mg of corn cobs available (Cao et al., 2004), which could feed 213 million animal units for 120 days, based on consuming 3% of their body weight (BW) on a dry matter basis with 20% corn cobs (DM basis) in the diets.

An increasing population and reduction in farmable land will require greater utilization of integrated crop-livestock systems and the use of crop residues to feed ruminants, which have the ability to change low-quality feed into high-quality products (Akram and Firincioğlu, 2019). Having a crop residue rich in anthocyanin can be even more appealing because it not only provides nutrients but also could be a functional feed (Tian et al., 2019).

Anthocyanin is a plant secondary metabolite with polyphenolic structures responsible for the blue, red, or purple pigments widely found in plants (Khoo et al., 2017; Tan et al., 2019). Recently, anthocyanins have gained popularity among researchers as a viable alternative to sustainable animal production (Suong et al., 2022) due to their antioxidant, anti-inflammatory, and antimicrobial properties (Tan et al., 2019; Tian et al., 2019; Prommachart et al., 2020). Additionally, dietary anthocyanin can decrease saturated fatty acids (SFA) and increase important polyunsaturated fatty acids (PUFA), which is a great advantage for consumers in terms of cardiovascular disease

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prevention (Siri-Tarino et al., 2015; Tian et al., 2022). The addition of antioxidants from natural supplements, such as anthocyanins, to animal diets is one strategy to reduce meat oxidation (Prommachart et al., 2021a; Tian et al., 2022), which maintains a more stable meat color over time (Maggiolino et al., 2021).

The corn breeding program of Texas A&M AgriLife has developed a new type of corn hybrids, named as Hi-A corn hybrids, which produce and accumulate extremely high anthocyanins and antioxidants in their cobs and other tissues in comparison to widely grown normal corn. The total anthocyanin content in Hi-A corn cobs is approximately 4.99 mg/g, which is 125 times greater than ordinary corn cobs (Low-A, ~0.04 mg/g). We hypothesized that adding anthocyanin-rich corn cobs to lamb diets can improve feedlot performance, carcass traits, and meat fatty acid profiles as well as prevent meat color discoloration under retail display and enhance meat aroma and sensorial characteristics. Thus, this study evaluated the effects of Hi-A corn cobs in feedlot lamb diets on intake, growth performance, carcass traits, meat color, fatty acid profiles, volatile aroma compounds, and sensory panels.

MATERIALS AND METHODS

Animals and Management

The feeding experiment was conducted at the Texas A&M AgriLife Research and Extension Center in San Angelo, TX. The experimental protocol was approved by the Texas A&M University Animal Care and Use Committee (2018-013A). Rambouillet female lambs (n = 30; approximate age = 8 months) were weighed (initial body weight, BW = 30.7 ± 1.2 kg), stratified by BW, and randomly assigned to one of three diets (n = 10/treatment). Lambs received an ear tag and subcutaneous injection of a clostridial vaccine (Bar-Vac, Boehringer Ingelheim Vetmedica, Duluth, GA, USA), drenched (with Albendazole, Valbazen, Zoetis, Parsippany, NJ, USA) and then randomly assigned to an individual, completely covered dirt pen (2.44 × 5.94 m) with feed bunks and automatic watering systems. The adaptation period to experimental diets was conducted in two steps and consisted of increasing levels of concentrate (50% and 65% DM total diet) over 14 d (7 d for each diet) until reaching 80% of concentrate in the finishing experimental diets according to the assigned treatment group. Non-pelleted diets containing 20% of one roughage (Hi-A corn cobs, Low-A corn cobs, or BGH) and 80% of concentrate containing 62.85% corn, 10% cotton seed meal, 4% molasses, 1.4% limestone, 0.75% mineral-vitamin premix, 0.5% ammonium chloride, and 0.5% salt were formulated to meet the nutrient requirements (NRC, 2007). Monensin (22 g/metric ton of Rumensin 90; Elanco, Indianapolis, IN) was included in all diets. The chemical composition of roughage and experimental diets are shown in Table 1. Lambs were individually fed once daily at 0800 h with a targeted refusal rate of 10% of offered feed. Diet refusals were collected daily and weighed to determine dry matter intake (DMI). Lamb BW was recorded on days 0, 14, 28, 42, 54, and 63. Average daily gain (ADG) and DMI were determined between days in which BW was recorded. Gain:feed ratio (G:F) was calculated by dividing the ADG by DMI.

Feed Collection and Analysis

Triplicate samples of roughage and the total mixed ratio of each treatment diet were collected, dried at 60 °C in a forced-air oven for 72 h, ground in a Wiley Mill (Arthur H. Thomas Co., Philadelphia, PA) to pass a 1 mm screen, and stored at –20 °C until analysis. Nitrogen (N) was analyzed using combustion method [Method 990.03 (AOAC, 2006)], and crude protein (CP) was calculated as 6.25 × N. Neutral and acid detergent fiber (NDF and ADF, respectively) were analyzed sequentially according to the procedures of Van Soest et al. (1991), which were modified for an Ankom 2000 Fiber Analyzer (Ankom Technol. Corp., Fairport, NY, USA), using α-amylase and sodium sulfite for NDF analysis. Standard methods were used to analyze lignin [973.18; (AOAC, 2006)], crude fat [2003.05; (AOAC, 2006)], and ash [942.05; (AOAC, 2006)]. Feed sulfur (S) was evaluated using a Leco (model SC-432, St. Joseph, MI) analyzer, and all other minerals were analyzed by a Thermo Jarrell Ash IRIS Advantage HX Inductively Coupled Plasma Radial Spectrometer (Thermo Instrument Systems, Inc., Waltham, MA).

Once a week, diet refusals were collected, air-dried, and stored in paper bags at room temperature with low humidity. Diet refusals dried quickly in the covered dirt pens due to the hot and dry conditions. We kept the samples in an air-conditioned room to prevent mold and protect the samples against the variations in temperature and moisture. At the end of the trial, material obtained from each animal was mixed and a subsample (~200 g) was taken to be analyzed as previously described. The remaining data were used for the particle size (PS) distribution analysis.

The PS distribution of the roughage, total mixed ration (TMR), and refusals were determined using a Penn State Particle Size Separator [PSPS, (Lammers et al., 1996)] according to modified procedures (Kononoff et al., 2003). The PSPS contains a series of three sieves and a solid bottom pan arranged in descending size (19.0, 8.0, and 1.18 mm sieves; Model C24682N, Nasco, Ft. Atkinson, WI, USA). Sample was placed onto the top sieve and after shaking according to standard procedures, remaining material on each sieve and in the bottom pan (0-mm) was weighed and oven-dried (Model 630, NAPCO, Portland, OR, USA) at 60 °C for 72 h to determine the retained DM. Amount of DM retained on each sieve, geometric mean particle length (Xgm), and standard deviation of particle length (Sgm) were calculated [method S424 (ASABE, 2007)]; particles were assumed to be logarithmically and normally distributed (Kononoff et al., 2003). Roughage and experimental TMR PS distribution using PSPS are presented in Table 1.

An Ankom model Daisy^{II} incubator was used to determine the roughage, TMR, and 48 h refusals in vitro dry matter digestibility (IVDMD) in separate F57 bags (Ankom Technol. Corp., Macedon, NY, USA). Three bags of roughage, three bags of TMR, and 10 bags of feed refusals from the same treatment were incubated in one jar using ruminal inoculum combined from lambs fed with the corresponding treatment. Two jars were used for each treatment. Each bag contained 0.4 g of sample that was hammer milled to pass a 1 mm screen (Wiley mill). Bags were placed into jars containing 400 mL of rumen fluid (collected orally with a stomach tube approximately 4 h after feeding) and 1,600 mL of McDougal's buffer solution [1.0 g of urea/L; (McDougall, 1948)]. Analysis began on day 62 and lasted 48 h. Two blank bags per jar were

Table 1. Chemical composition, in vitro dry matter digestibility (IVDMD) and particle size distribution of the ingredients and total *mixed* ration (TMR) used in the experiment

Item[1]	Ingredient			TMR		
	HI-A	LOW-A	BGH	HI-A	LOW-A	BGH
CP, %	5.53	6.60	8.77	13.0	13.5	14.9
NDF, %	72.7	71.8	70.8	24.6	22.5	21.1
ADF, %	35.3	37.7	37.8	11.8	12.0	10.9
Lignin, %	5.60	5.03	5.07	2.53	2.47	2.30
Ash, %	2.14	2.49	8.76	5.08	5.10	5.78
IVDMD, %	44.5	50.3	60.6	76.5	79.8	81.8
Anthocyanin, g/kg	4.99	0.04	0.00	1.00	0.01	0.00
Ca, %	0.14	0.04	0.34	0.45	0.50	0.58
P, %	0.12	0.18	0.20	0.33	0.34	0.40
Mg, %	0.07	0.10	0.16	0.16	0.16	0.18
K, %	0.62	0.86	2.20	0.81	0.90	1.09
Na, %	0.11	0.03	0.07	0.33	0.35	0.39
S, %	0.08	0.09	0.33	0.20	0.21	0.25
Fe, ppm	120	103	280	115	129	182
Zn, ppm	22.3	26.0	28.3	54.0	82.7	54.3
Cu, ppm	3.33	4.67	6.00	3.33	4.67	4.00
Mn, ppm	9.00	14.0	102	27.0	41.0	42.3
Mo, ppm	0.57	0.67	2.93	0.43	0.40	1.00
Sieves, % retained						
19 mm	0.0	0.0	51.1	0.0	0.0	9.10
8 mm	0.6	0.0	21.9	5.8	1.5	14.2
1.18 mm	66.1	65.7	17.6	63.6	58.8	57.4
Pan, 0 mm	33.4	34.3	9.3	30.6	39.6	19.2
Xgm, mm	2.25	2.20	19.9	2.49	2.08	4.29
Sgm, mm	2.03	2.02	4.54	2.19	2.12	3.28

[1]Results are expressed in dry matter basis. Xgm = geometric mean particle length; Sgm = standard deviation of particle length.

included to adjust for potential residue, and two bags of alfalfa with known IVDMD were included as internal controls. After anaerobic incubation at 39 °C, bags were gently rinsed under cold water for 5 min, subjected to the NDF procedure as previously described, dried at 60 °C in a forced-air oven (Model 630, NAPCO, Portland, OR, USA) for 48 h, and weighed to calculate the disappearance.

Carcass Characteristics, Meat Color and Fatty Acids

On day 63, lambs were transported 465 km to Texas A&M University at College Station and humanely harvested after a 24 h fast. Shrunken BW and hot carcass weight (HCW) were measured by weighing fasted lambs and carcasses, respectively. Next, carcasses were chilled at 2 ± 1 °C. Then, at 48 h postmortem, each carcass was ribbed between the 12th and 13th ribs and analyzed to determine longissimus muscle area (LMA), backfat thickness (BFT) at the 12th rib, body wall thickness (BWT), and leg circumference (LC) across the stifle joint (USDA, 1997). The dressing percentage (DP) was calculated (HCW/shrunk BW) × 100.

Longissimus muscle (LM) was removed from the left side of each carcass by deboning from the thoracic vertebrae according to procedures of the North American Meat Processors [232a (NAMP, 1997)]. Six 2.54 cm-thick chops were cut starting from the posterior end. The first chop, designated for fatty acid methyl ester (FAME) analysis, was cut to straighten the LM face, separately vacuum packaged, and stored at −80 °C. Subsequently, five 2.54 cm-thick chops were serially cut for color measurements in a retail display and volatile aroma compounds and the last three chops were used for sensory panel analysis. For the retail display, samples were immediately placed in 21.0 cm × 14.6 cm × 1.27 cm white foam meat trays (Genpak 17S Styrofoam tray, Alliance Paper & Food Service, Franklin Park, IL) and overwrapped with polyvinyl chloride film. The remaining samples were labeled, vacuum packaged, and stored at −10 °C.

The trays with fresh chops were placed in a retail display with a temperature of 4 °C and lights (F 40 T 12; 40 W, Alto Collection, Philips Electronics America Corporation, Andover, MA) that were adjusted to give 1,000 lx illumination at the chop surface. Instrumental color measurements were taken daily for 7 d using a portable colorimeter (Hunter Miniscan XE Plus MSXEt, Hunter Laboratories, Reston, VA) with a 10° observation angle, D65 illuminant, and 3.5 cm aperture. Color measurements were collected in two locations for an average measurement of L*, a*, and b* color values. Hue and chroma were calculated using the formulas (tan − 1[(b*/a*)]) and $(a^2 + b^2)1/2$, where larger angles are more yellow and discolored and the saturation index, where larger values represent a more intense color.

For FAME analysis and after the LM cross-section samples were pulverized in liquid nitrogen, including any residual intermuscular fat, the total lipids were extracted using a modification of the method outlined in Folch et al. (1957). Adipose tissue (100 mg) was extracted in chloroform:methanol (2:1, vol/vol), and the FAME analysis was prepared as described by Morrison and Smith (1964) but modified to include an additional saponification step (Archibeque et al., 2005). The FAME analysis was conducted using a Varian gas chromatograph (GC; model CP-3800 fixed with a CP-8200 autosampler; Varian, Inc., Walnut Creek, CA). Separation of the FAME was accomplished on a fused silica capillary column CP-Sil88 [100 m long × 0.25 mm i.d.; Chrompack, Inc., Middleburg, the Netherlands; helium as carrier gas (flow rate = 1.2 mL/min)]. After 32 min at 180 °C, oven temperature was increased from 20 °C/min to 225 °C and held for 13.8 min; total run time was 48 min. Injector and detector temperatures were 270 °C and 300 °C, respectively. Individual FA was identified using the GLC-68D genuine external standard (Nu-Chek Prep, Inc., Elysian, MN). Individual FA was quantified as a percentage of the total FAME analyzed.

Meat Volatile Aroma Compounds and Sensory Panel

For sensory analysis, chops were thawed in a refrigerator at 4 °C for 12–24 h and then cooked on a 91.44-cm flat top with an electric griddle with snap action thermostatic controls (Star Max Countertop 536TGF, Star International Holdings Inc. Company, St. Louis, MO) set at 177 ± 2.8 °C. The grill temperature was monitored using a handheld instantaneous surface thermometer (Pro-Surface ThermaPen, SKU: #THS-231-279, ThermoWorks, American Fork, UT). Chops were turned over and removed when the internal temperature reached 35 °C and 71 °C, respectively [i.e., a medium degree of doneness (AMSA, 2016)]. Internal meat temperatures were monitored by iron-constantan thermocouples (Omega Engineering, Stanford, CT) with a temperature display (Omega HH501BT Type T, Omega Engineering, Stamford, CT) inserted into the geometric center of the sample. The cook loss was expressed as a percentage of post-cooking weight loss from the raw weight. A trained panel of meat flavor descriptive attribute experts (i.e. 38 basic flavors and 3 texture attributes (Adhikari et al., 2011), consisting of 6 panelists [STP758 (ASTM, 1981)] scaled each attribute on a 16-point scale (Hough et al., 2006; AMSA, 2016). The utilization of human subjects to analyze sensory attributes of the lamb meat was approved by the Texas A&M University Institutional Review Board number IRB2017-0618. A "warm-up" sample chop was served at the initiation of each sensory session. Next, two random representative cubes (1.3 cm × 1.3 cm × chop thickness) of a sample were served to panelists in a plastic souffle cup at a round table under red lighting. The outer edges and fat were avoided when cutting the chops. Saltless crackers and double-distilled water were offered as palette cleansers. Panelists tested 11 samples per day (i.e. five samples followed by a break, then six in the second hour) for 3 d total (Bohnenkamp and Berry, 1987; AMSA, 2016). Panelists evaluated each sample individually and recorded their score for the attribute on the ballots. Chops were evaluated for brown roasted, salty, sweet, bitter, sour, umami, fat like, bloody serum, metallic, liverlike, cardboardy, musty earthy, lanolin animal hair, mutton, green, juiciness, muscle fiber tenderness, and connective tissue (ASTM, 1981; Bohnenkamp and Berry, 1987; Hough et al., 2006; Adhikari et al., 2011; AMSA, 2016).

Volatile aroma compounds were determined by placing cooked 1 cm × 1 cm × chop thickness LM cubes in heated glass jars (473 mL) with a Teflon lid under the metal screw-top to avoid off-aromas and then set in a dry sample incubator at 60 °C. Next, the headspace was collected with a solid-phase microextraction (SPME) portable field sampler (Supelco 504831, 75 µm Carboxen/polydimethylsiloxane, Sigma–Aldrich, St. Louis, MO). The static headspace above each meat sample in the glass jar was collected for 2 h. After collection, each SPME was injected (splitless mode) in the injection port of a gas chromatograph (GC; Agilent Model 6920, Santa Clara, CA) where the sample was desorbed at 280 °C. Next, the sample was loaded onto a GC column (Agilent VF 5MS 30 m long × 0.25 mm ID/1 µ film thickness, SGE Analytical Sciences, Austin, TX). Through the column, the temperature started at 40 °C (held for one minute) and increased at a rate of 20 °C/min until reaching 250 °C. Compounds were identified and quantified with a mass spectrometer (MS; Agilent Technologies 5975 series MSD, Santa Clara, CA) using the NIST/Wiley Chemical Library (Palisade, Ithaca, NY, USA). Normalized [log10 (n + 1)] MS total ion count areas under the curve of each compound peak were transformed for statistical analyses.

Statistical Analysis

Lamb BW, ADG, DMI, G:F, and meat instrumental color were analyzed by ANOVA using the PROC MIXED procedure of SAS (SAS Inst. Inc., Cary, NC) with a model that included treatment, day, and treatment × day interaction; the day was a repeated measure and individual lambs were the subject. When a treatment × day interaction was observed ($P < 0.05$), the effects were evaluated by day. The PSPS data were analyzed by ANOVA using the PROC MIXED procedure of SAS (SAS Inst. Inc., Cary, NC) with a model that included treatment, sieve, and treatment × sieve interaction. When a treatment × sieve interaction was observed ($P < 0.05$), the effects were evaluated by the sieves. Suitable covariance structures were compared for each model. Refusal chemical composition, carcass traits, meat fatty acids, volatile aroma compounds, and sensory panel characteristics were analyzed by one-way ANOVA using SAS (SAS Inst. Inc., Cary, NC) with a model that included the diet as the fixed effect and lamb as the experimental unit. Sensory panel data were checked by a panelist for treatment interactions, and when none were present ($P > 0.05$), panelist scores were averaged for each experimental unit (lamb). All data are reported as least squares means with the greatest SEM. Statistical significance was declared at $P \leq 0.05$, and a tendency was declared at $0.05 < P \leq 0.10$.

RESULTS

Feedlot Performance

The diet refusals of Hi-A and Low-A had less NDF ($P < 0.0001$) and ADF ($P < 0.0001$) and greater IVDMD ($P = 0.002$) than BGH; however, Hi-A and Low-A did not differ ($P > 0.05$) (Table 2).

The interaction treatment × sieve affected ($P < 0.001$) particle size distribution of diet refusals (Table 2). Hi-A and

Low-A had similar ($P > 0.05$) particle size distributions; conversely, both had less and greater percentages of particles >19 mm and <1.18 mm than BGH, respectively ($P \leq 0.05$). The Dgm and Sgm of Hi-A and Low-A refusals were less ($P < 0.01$) than BGH diet but were similar ($P > 0.05$).

The interaction treatment × day did not affect ($P > 0.05$) intake or growth performance; however, isolated effects on response variables were observed (Table 3). Although diet did not affect BW, ADG, or G:F of the lambs, lambs fed BGH diet had a less DMI ($P = 0.004$) than lambs fed diets with either type of corn cob. Both BW and DMI of the lambs increased ($P < 0.01$) in the final part of the feedlot period after 42 d in the feedlot. ADG and G:F of the lambs were less ($P < 0.01$) from days 28 to 42 compared to the rest of the feedlot time. In addition, G:F of the lambs was greater from days 0 to 14 compared to after day 56.

Carcass Traits, Meat Color, and Meat Fatty Acids

There was no difference ($P > 0.05$) among diets for all evaluated carcass traits (i.e. HCW, LMA, BWT, BFT, leg score, marbling, skeletal maturity, lean maturity, and flank streaking) except by DP ($P = 0.04$), which was greater when lambs were fed BGH compared to Hi-A, while lambs fed Low-A did not differ ($P > 0.05$) from them (Table 4).

Instrumental color characteristics of fresh lamb loin chops were not affected ($P > 0.05$) by diet × day (Table 5). There was no effect of diet on L*, a*, b*, or chroma ($P > 0.05$). Conversely, the meat from lambs fed Hi-A corn cobs had a greater ($P = 0.05$) hue angle than that from lambs fed Low-A corn cobs, while lambs fed BGH did not differ from lambs fed any type of corn cob diet ($P > 0.05$). All instrumental meat color parameters were affected by the day. The L* was greater ($P = 0.01$) on day 1 than on days 0, 3, and from days 5 to 7,

Table 2. Neutral (NDF) and acid detergent fiber (ADF), in vitro dry matter digestibility (IVDMD) and particle size distribution of ration refusals of lambs fed high anthocyanin corn cobs (Hi-A), regular corn cobs (Low-A), or bermudagrass hay (BGH)

Item[1]	Diets					*P*-value	
	Hi-A	Low-A	BGH	SEM	Diet	Screen	Diet × screen
Composition, %							
NDF	25.3^{b}	22.9^{b}	44.8^{a}	4.64	<0.01		
ADF	11.2^{b}	10.0^{b}	20.5^{a}	2.17	<0.01		
IVDMD	74.2^{a}	75.5^{a}	69.0^{b}	1.32	0.01		
Particle size, %							
19 mm	0.00^{bB}	0.01^{bB}	57.4^{aA}	6.68	0.99	<0.01	<0.01
8 mm	2.30^{aB}	1.67^{aB}	15.7^{aB}				
1.18 mm	49.8^{aA}	47.4^{aA}	4.80^{bB}				
Pan (0 mm)	47.9^{aA}	50.9^{aA}	22.1^{bB}				
Dgm, mm	1.96^{b}	1.82^{b}	19.9^{a}	5.01	<0.01		
Sgm, mm	2.02^{b}	2.10^{b}	5.22^{a}	0.53	<0.01		

[1]Results are expressed in dry matter basis. Xgm = geometric mean particle length; Sgm = standard deviation of particle length.
^{ab}Least squares means in same line with different superscripts are statistically different ($P \leq 0.05$).
^{AB}Least squares means in same column with different superscripts are statistically different ($P \leq 0.05$).

Table 3. Feedlot final body weight (BW), average daily gain (ADG), dry matter intake (DMI), and gain:feed ratio (G:F) of lambs fed high anthocyanin corn cobs (Hi-A), regular corn cobs (Low-A), or bermudagrass hay (BGH)

Item	BW, kg	ADG, kg/d	DMI, kg/BW$^{0.75}$	G:F
Diet				
Hi-A	38.1	0.20	80.4^{a}	0.17
Low-A	38.6	0.21	80.5^{a}	0.19
BGH	38.7	0.18	71.6^{b}	0.18
SEM	0.83	0.01	3.05	0.01
P-value	0.64	0.42	0.004	0.53
Feedlot day				
14	33.7^{c}	0.21^{a}	69.4^{b}	0.23^{a}
28	36.6^{b}	0.23^{a}	72.4^{b}	0.21^{ab}
42	38.0^{b}	0.12^{b}	74.6^{b}	0.11^{c}
56	41.3^{a}	0.24^{a}	86.5^{a}	0.18^{ab}
63	42.7^{a}	0.19^{a}	84.5^{a}	0.17^{b}
SEM	0.92	0.02	3.40	0.01
P-value	<0.01	<0.01	<0.01	<0.01

^{abc}Least squares means in same column with different superscripts are statistically different ($P \leq 0.05$) regarding diet or feedlot day.

Table 4. Carcass traits of lambs fed high anthocyanin corn cobs (Hi-A), regular corn cobs (Low-A), or bermudagrass hay (BGH)

Item[1]	Diets			SEM	*P*-value
	Hi-A	Low-A	BGH		
HCW, kg	20.7	21.3	21.8	0.59	0.45
DP, %	52.7^{b}	54.6^{ab}	55.3^{a}	0.72	0.04
LMA, cm	15.5	15.5	16.8	1	0.67
BWT, cm	1.7	1.7	1.8	0.1	0.75
FT, cm	0.48	0.53	0.53	0.05	0.71
Leg Score[2]	11.4	11.7	11.9	0.4	0.68
Marbling[3]	343.4	384.4	379.4	21	0.33
Skeletal maturity[4]	150.3	153.3	141.3	6.4	0.4
Lean maturity[4]	144.7	155.4	148.7	6.1	0.44
Flank Streaking[5]	401.1	412.1	458.1	21.9	0.17

[1]HCW = hot carcass weight; DP = dressing percentage; LMA = loin muscle area; BWT = back wall thickness; FT = fat thickness.
[2]Leg score 11 = Choice^{+}, 13 = Prime^{o}.
[3]Marbling 300 = Slight^{00}, 500 = Modest^{00}.
[4]Skeletal/Lean maturity 100 = A^{00}.
[5]Flank streaking 300 = Slight^{00}, 500 = Modest^{00}.
^{abcd}Least squares means in a column within corn cob diet or display day with different superscripts are statistically different ($P \leq 0.05$).

Table 5. Instrumental color characteristics of fresh lamb loin chops of lambs fed high anthocyanin corn cobs (Hi-A), regular corn cobs (Low-A), or bermudagrass hay (BGH)

	L*[1]	a*[1]	b*[1]	Chroma[2]	Hue angle[2]
Diet					
Hi-A	33.8	16.3	14.1	21.7	41.1^{a}
Low-A	32.7	17.0	14.2	22.2	39.7^{b}
BGH	34.0	16.8	14.4	22.2	40.8^{ab}
SEM	0.92	0.54	0.46	0.36	0.39
P-value	0.57	0.66	0.89	0.46	0.04
Retail display day					
0	32.7^{bc}	19.6^{a}	14.4^{bcd}	24.3^{ab}	35.9^{d}
1	35.2^{a}	18.8^{a}	16.1^{a}	24.8^{a}	40.6^{bc}
2	32.9^{bc}	17.0^{b}	15.1^{b}	22.7^{bc}	41.7^{ab}
3	33.7^{b}	16.0^{c}	14.8^{b}	21.8^{cd}	42.9^{a}
4	34.5^{ab}	15.1^{d}	14.0^{c}	20.7^{de}	43.1^{a}
5	32.6^{c}	16.0^{c}	13.7^{c}	21.1^{cde}	40.6^{bc}
6	33.5^{b}	15.7^{cd}	13.2^{de}	20.5^{de}	39.9^{c}
7	33.0^{bc}	15.5^{cd}	12.8^{e}	20.2^{e}	39.6^{c}
SEM	0.95	0.86	0.72	0.58	0.64
P-value	0.0056	<0.0001	<0.0001	<0.0001	<0.0001

[1]L* is a measure of darkness to lightness (greater L* values indicate a lighter color); a* is a measure of redness (greater a* values indicate a redder color); and b* is a measure of yellowness (greater b* values indicate a more yellow color).
[2]Chroma is a measure of the total color of the sample (greater chroma values indicate a more vivid color); Hue angle is a measure of discoloration of the sample (greater hue angle values indicate more discoloration).
^{abcde}Least squares means in a column within corn cob diet or display day with different superscripts are statistically different ($P \leq 0.05$).

while it was similar ($P > 0.05$) to that on day 4. The greatest a* was obtained on days 0 and 1 ($P < 0.01$); after that, it was reduced, reaching the lowest values on days 4, 6, and 7 ($P < 0.01$). Maximum b* was observed on day 1 ($P < 0.01$) and then declined afterward ($P < 0.01$), reaching the lowest values on the last two days (i.e. days 6 and 7). Chroma was greater ($P < 0.01$) on the first two days (days 0 and 1) than those obtained from days 3 to 7. The hue angle was greater ($P < 0.01$) from days 2 to 4 compared to days 5 and 7, while the lowest value occurred on day 0 ($P < 0.01$).

Nineteen FA were detected in the lamb meat (Table 6) by the standard analytical method. No differences ($P > 0.05$) in the FA concentrations of the meat of lambs fed Hi-A, Low-A, or BGH were detected.

Sensory Panel and Meat Aroma

Sensory panel lamb flavor identity tended ($P = 0.10$; Table 7) to be higher in lambs fed BGH than in Low-A, and juiciness scores tended ($P = 0.08$) to be higher in lambs fed High-A

Table 6. Fatty acids profile in the meat of lambs fed high anthocyanin corn cobs (Hi-A), regular corn cobs (Low-A), or bermudagrass hay (BGH)

Fatty acid, %	Diets			SEM	*P*-value
	Hi-A	Low-A	BGH		
C14:0	3.26	3.47	3.20	0.10	0.52
C14:1	0.19	0.23	0.20	0.01	0.29
C16:0	22.5	22.7	22.4	0.17	0.87
C16:1	1.70	1.81	1.69	0.03	0.18
C18:0	12.6	12.0	12.4	0.21	0.47
C18:1C9	36.6	37.7	37.8	0.38	0.37
C18:1C11	1.00	0.69	0.73	0.10	0.39
C18:2	6.90	6.09	6.61	0.20	0.24
C18:3	0.52	0.62	0.66	0.03	0.09
C20:0	0.14	0.14	0.16	0.00	0.12
C20:1	0.18	0.20	0.19	0.00	0.23
C20:2	0.06	0.06	0.06	0.00	0.32
C20:3	0.05	0.05	0.04	0.00	0.61
C20:4	2.60	2.40	2.31	0.10	0.30
C20:5	0.36	0.36	0.39	0.02	0.87
C22:0	0.03	0.03	0.03	0.00	0.96
C24:0	0.05	0.05	0.05	0.01	0.96
C24:1	0.62	0.61	0.60	0.02	0.86
C22:6	0.25	0.25	0.23	0.01	0.86

Table 7. Sensory analysis of boneless loin chops from lambs fed high anthocyanin corn cobs (Hi-A), regular corn cobs (Low-A), or bermudagrass hay (BGH)

Item	Diets			SEM	*P*-value
	Hi-A	Low-A	BGH		
Cook loss, %	19.0	20.7	22.6	1.49	0.26
Lamb identity	6.6	6.3	6.9	0.21	0.10
Brown roasted	6.4	6.7	6.5	0.33	0.73
Salty	1.7	1.7	1.7	0.17	0.93
Sweet	0.3	0.4	0.4	0.12	0.90
Bitter	1.6	1.6	1.7	0.11	0.66
Sour	1.9	1.7	1.7	0.10	0.51
Umami	3.9	3.9	3.8	0.19	0.95
Fat like	1.6	1.3	1.5	0.14	0.56
Bloody serum	1.6	1.3	1.3	0.25	0.56
Metallic	2.9	2.7	2.8	0.13	0.57
Liverlike	1.2	1.1	1.5	0.18	0.36
Cardboardy	0.1	0.4	0.2	0.13	0.27
Musty earthy	1.1	1.2	1.2	0.13	0.73
Lanolin animal hair	0.2	0.3	0.5	0.16	0.44
Mutton	1.2	1.2	1.4	0.25	0.90
Green/hay like	0.1	0.1	0.0	0.08	0.43
Juiciness	8.2	8.0	7.4	0.25	0.083
Muscle fiber tenderness	11.9	11.9	12.0	0.30	0.92
Connective tissue	12.7	12.6	12.6	0.20	0.95

than in BGH, but diet had no effect ($P > 0.25$) on either cook-loss percentage or other sensory panel traits.

Five meat volatile compounds were affected by diets (Table 8). The 2-butanone tended ($P = 0.07$) to be greater and 2,3-butanedione was greater ($P = 0.05$) in chops from lambs fed BGH than those fed the Hi-A corn cob, neither of which differed ($P > 0.05$) from lambs fed the Low-A diet. The compound 2-propanone was greater ($P = 0.01$) in chops from

Table 8. Least squares means of log10 (n + 1) area under the curve total ion count of volatile aroma compounds of boneless loin chops from lambs fed high anthocyanin corn cobs (Hi-A), regular corn cobs (Low-A), or bermudagrass hay (BGH)

Volatile compounds	Diets			SEM	*P*-value
	Hi-A	Low-A	BGH		
2-Butanone[1]	5.9[b]	8.6[ab]	13.2[a]	2.16	0.07
2-Propanone[1]	13.3[b]	13.5[b]	14.2[a]	0.21	0.01
2,3-Butanedione[2]	5.5[b]	6.7[ab]	11.1[a]	1.62	0.05
3-Methyl-butanal[3]	12.6[b]	13.7[a]	14.0[a]	0.32	0.01
Methyl benzene[2]	1.0[b]	7.8[a]	7.9[a]	1.93	0.02

[1]Lipid degradation product.
[2]Maillard reaction product.
[3]Strecker aldehyde.
[ab]Least squares means within a line with different superscripts are statistically different ($P < 0.05$).

lambs fed the BGH than those fed either the Low-A or Hi-A diets, which were similar ($P > 0.05$). Both 3-methyl-butanal and methyl benzene were lower ($P = 0.01$ and $P = 0.02$, respectively) in chops from lambs fed the Hi-A than those fed either BGH or Low-A diets, which were similar ($P > 0.05$).

DISCUSSION

In this work, we investigated a novel type of corn with cobs rich in anthocyanin as roughage in feedlot lamb diets in comparison to regular corn cobs and commonly used grass hay for comparison. In accordance with the literature (Prommachart et al., 2021b; Antunović et al., 2022; Tian et al., 2022), there was no effect of dietary anthocyanin on lamb DMI and growth performance. Prommachart et al. (2021b) also found no differences in DMI when black rice and purple corn-extracted residue were tested in the diets of male dairy cattle. Antunović et al. (2022) observed no influence of red corn rich in anthocyanins in lamb diets on final BW, ADG, and DMI. Tian et al. (2022) did not find the effects of feeding goats purple corn anthocyanin on DMI, ADG, or G:F.

Regardless of the corn variety, utilization of corn cobs as a roughage in lamb diets resulted in AGD and G:F ratios comparable to BGH (Matsushima et al., 1957; Reddy and Reddy, 1991; Wachirapakorn et al., 2016). At the 12,553 kg/ha grain yield level, one hectare of corn field can produce up to 5,609 kg/ha of corn cobs, while bermudagrass usually produces 11,218–15,706 kg/ha of hay with good management under favorable soil moisture conditions. Therefore, corn cobs can be an alternative feed supply for small ruminants (Reddy and Reddy, 1991), dairy (Wachirapakorn et al., 2016), and beef cattle (Matsushima et al., 1957) as well as a new source of income for corn producers.

The comparison of TMR and orts composition was used to estimate the consumed nutrients (Fisher, 1979). In this context, orts of the BGH diet differed from those of the corn cob diets, regardless of the variety. The orts of BGH diets had 112% and 107% more NDF and ADF, respectively, than the TMR offered, while IVDMD decreased by 14.2%. In comparison, corn cob diets had only 13.3% more NDF and 10.9% and 4.8% less ADF and IVDMD, respectively, in the orts compared to the TMR. These differences may reside in the distinct physical characteristics of the roughage and sorting behavior (Quadros et al., 2022). Sheep are known for their sorting behavior, being more intense than cattle and less intense than goats, which may result in an unbalanced intake of nutrients (i.e. not consuming enough or overconsumption), reduction of the nutritive value of the ration, alteration of rumen fermentation, unexpected performance, and increased risks of rumen disorders (Miller-Cushon and DeVries, 2017; Sari et al., 2018).

Because of the PSPS characteristics of the BGH TMR, which had an average particle size 1.9 times longer than cob diets, which was mainly due to the proportion of particles retained at 19 mm and 8 mm PSPS sieves, animals could sort more easily than when corn cob diets were offered. For instance, refusals from BGH diets had 6.3-fold particles retained in the 19 mm sieve (i.e. hay) compared to the TMR, which was higher in fiber and lower in digestibility than particles < 8 mm (i.e. concentrate). In comparison with BGH, corn cob refusals had approximately 53% less NDF and ADF and 8.5% higher IVDMD. In contrast to BGH, which was chopped, corn cobs were chopped and hammermilled, which allowed a more homogenous TMR mix. Grinding and mixing feed ingredients are common and effective practices to reduce sorting by feedlot lambs, knowing that particle size is one of the primary factors that influences feed sorting with longer particles being more easily sorted than shorter particles (Miller-Cushon and DeVries, 2017; Quadros et al., 2022). The sorting index of the material remaining in the bottom pan of BGH diets, which was calculated as the actual DMI of each fraction of the PSPS divided by the predicted DMI of that fraction (Leonardi and Armentano, 2003), was 126%; this indicates that the lambs sorted for it. Indeed, feedlot lambs sort most against the longest particles and fine particles (Sari et al., 2018). Therefore, the capacity of animals that sorted for the concentrate when fed BGH influenced DMI so that they could consume less ration and maintained similar growth performance compared to cob diets.

Although anthocyanins are phenolic compounds that may contribute to the bitter flavor of plants (Khonkhaeng and Cherdthong, 2019), in this trial, the anthocyanin concentration did not change the sorting behavior or DMI between the two varieties of corn cobs, which corroborated the findings of Tian et al. (2019) and Prommachart et al. (2021b). Lambs fed either Hi-A or Low-A corn cobs had the same estimated daily intake of ADF (0.15 kg) and digestible DM (i.e. IVDMD, 0.99 kg), which corroborated with Prommachart et al. (2021b). Apparently, anthocyanins neither effect digestibility when the nutrient balance is unchanged (Tian et al., 2019, 2021a), nor do most rumen bacteria with a relative

abundance > 1% at the genus level (Tian et al., 2021a) or volatile fatty acids (Suong et al., 2022).

However, the estimated NDF daily intake was 33% greater when lambs were fed Hi-A than Low-A, which was probably due to a lack of a direct relationship with the anthocyanin concentration itself (Prommachart et al., 2021b; Tian et al., 2022), but the Hi-A and consequently TMR chemical composition did have an influence. Hosoda et al. (2012) reported that purple rice silage contains abundant anthocyanin and has inadequate nutritional values compared to control rice silage, including higher levels of fiber fractions and lower nutrient digestibility. This suggests that a new variety with good nutritional value is needed. The increased NDF could lead to decreased DMI according to the rumen fill hypothesis (Allen, 1997). Although this could be acceptable for a high-forage diet when high-energy diets are fed, DMI is controlled by the physiological energy demand of the animal and the psychogenic mechanism (Mertens, 1987).

From days 28 to 42, a heat wave affected the growth performance in all treatments with temperatures greater than normal. These temperatures reached greater than 37 °C for five consecutive days, which is above thermal comfort zone of 12–32 °C reported for sheep (Ames, 1980). The thermal environment is known as a major factor that negatively affects sheep performance (Al-Dawood, 2017). Increased body temperature is associated with a reduction in feed intake, redistribution in blood flow, and changes in endocrine functions that will negatively affect productive and reproductive performance (Mahjoubi et al., 2015). Compared to other breeds (e.g. Karakul, St. Croix, Chokla, and Malpura), Rambouillet showed physiological signs, such as rectal temperature and respiratory rates, indicating that it is not well adapted to intense summer heat (Singh et al., 1980; Monty Jr et al., 1991), which can further aggravate the deleterious effects of heat stress on growth performance in all experimental diets. Although antioxidant and anti-inflammatory activities of anthocyanin can minimize oxidative stress and improve the health status of ruminants under heat stress (Santos et al., 2019; Tian et al., 2021b) and considering the parameters evaluated in this trial, no difference in the use of anthocyanin in the lamb diets for coping with heat stress was observed.

The increase in BW and DMI and the reduction in G:F in the final part of the feedlot were somewhat expected based on beef cattle (Galyean et al., 2011; Cassady et al., 2016; Spowart et al., 2022) and sheep (Lane and Kemp, 1990; Claffey et al., 2018) trials, which showed feed efficiency declines with heavier weights and higher levels of body fat. Similarities in the feedlot growth performance, such as BW and ADG, among treatments led to the absence of effects on most carcass traits (i.e. HCW, LMA, BWT, BFT, leg score, marbling, skeletal maturity, lean maturity, and flank streaking). However, DP was 3.5% greater when lambs were fed BGH compared to Hi-A diets, while Low-A did not differ. Other studies with anthocyanin in lamb (Maggiolino et al., 2021) and goat meat (Suong et al., 2022) diets did not report any effect on carcass traits such as HCW, DP, BFT, and LMA.

Two common ways of selling commercial finished lambs in the U.S. are used, which are based either on liveweight or carcass weight (Beermann et al., 1995), the slightly lower DP of lambs fed Hi-A diets would make no difference compared to the other two diets because all diets had equivalent final BW and HCW. In addition, DP does not directly affect quality or yield grades (USDA, 1992), which is also followed by the U.S. lamb industry value-based pricing system (Whaley et al., 2019). Nonetheless, DP is an important factor for packers that pay based on liveweight or direct selling when the producers sell carcasses (or primal cuts) directly to consumers.

It is challenging to explain the reasons for the lower DP in lambs fed the Hi-A diet because final BW, which explains the largest amount of variation in HCW [r^2 = 0.83 (Hopkins, 1991)], and other carcass traits, such as BWT and BFT that could alter cutability (Whaley et al., 2019), were statistically equal. The greater NDF daily intake of lambs fed Hi-A (0.3 kg) compared to Low-A (0.23 kg) and BGH (0.21 kg), together with the lower IVDMD of Hi-A, may negatively influence the DP. Moreover, as previously discussed, the accentuated sorting behavior and lowest NDF daily intake of lambs fed BGH diets probably contributed to maximizing DP. According to Mirzaei-Alamouti et al. (2021), increasing NDF in feedlot lamb diets linearly decreased DP. Increased lamb dietary NDF resulted in heavier gastrointestinal tract weight, which negatively affects DP (Moura et al., 2019; Godínez-Olmedo et al., 2022). In addition, increasing NDF in feedlot lamb diets can increase gut fill, which reduces DP because less digestible and fibrous digestive content remains longer in the gastrointestinal tract during preslaughter fasting period (Medeiros et al., 2008).

Meat color in retail displays has a critical influence on consumer purchasing decisions due to its association with quality and freshness (Corlett et al., 2021). No instrumental color characteristics of fresh lamb loin chops were significantly modified by the different diets except the hue angle, which partially disagrees with the work of Prommachart et al. (2021a) when increasing amounts of extracts of anthocyanin from black rice and purple corn in cattle diets were tested. According to these authors, while beef lightness (L*) was not affected, redness (a*), yellowness (b*), and chroma were reduced in most days of evaluation up to 14 days of storage. However, in agreement with the present trial, Prommachart et al. (2021a) noticed a decrease in the hue angle when anthocyanins were increased in the diets. Apparently, the expectation of enhanced meat color with the use of a pigment, such as anthocyanin in the animal diet, has not been confirmed by research. Jerónimo et al. (2012) did not observe changes in any lamb meat color parameter when fed grape seed extract rich in anthocyanins. Inclusion of purple rice-rich anthocyanins in pork diets did not modify meat L*, a*, and b* (Jaturasitha et al., 2016). In broiler diets, increasing grape pomace rich in anthocyanins linearly decreased redness and resulted in paler meat (Kasapidou et al., 2016; Aditya et al., 2018).

Several factors can affect the stability of anthocyanins including but not limited to pH, temperature, oxygen, light intensity, and enzymes (McGhie and Walton, 2007). Anthocyanins change color with pH (Khoo et al., 2017), which limits their effective use for many applications (Wrolstad et al., 2005). In addition, chemical forms and biological activities of anthocyanins may be different when exposed to different pH values and temperatures in the gastrointestinal tract (Tian et al., 2021b). However, anthocyanins apparently have high stability in ruminal fluid, which increases the potential as a functional feed for ruminants (Hosoda et al., 2012; Song et al., 2012).

Although the effect of anthocyanins on enhancing meat color has not been proven, several authors have reported that antioxidants can protect meat against lipid oxidation

and consequently prolong shelf life (Yang and Zhai, 2010; Jerónimo et al., 2012; Lorenzo et al., 2018; Simitzis et al., 2019; Manessis et al., 2020). However, feeding Hi-A corn cobs to lambs did not reduce oxidative discoloration of the meat exposed in retail display, which is inconsistent with previous reports (Maggiolino et al., 2021 and Prommachart et al., 2021a). According to Maggiolino et al. (2021), dietary inclusion of a red orange and lemon extract rich in anthocyanins in suckling lamb diets enhanced meat oxidative stability and reduced color deterioration during aging. In addition, Prommachart et al. (2021a) observed more stable beef during storage time regarding b* and chroma, despite an increase in a* and hue angle.

During the trial, the concentration of anthocyanin in the diet (0.01%), anthocyanin release from the cobs or anthocyanin absorption and transport from the feed to the muscle may be factors that contribute to the lack of diet effects on meat color stability. In addition, anthocyanins as coloring agents may have accumulated in the fat stores (Jaturasitha et al., 2016); however, the fat color was not measured. Additionally, the reason for the variable results of anthocyanin in animal diets and effects on meat color may be related to the low bioavailability of anthocyanins in animals (Tian et al., 2021b).

As expected (Mancini and Hunt, 2005; Maggiolino et al., 2021; Prommachart et al., 2021a), the instrumental color characteristics were affected by the storage time. On the first day, L*, a*, b*, and chroma reached their peaks and then decreased over time. During the storage period, meat color deteriorates from red to brown due to the myoglobin concentration and redox status, while lightness increases with the passage of water from the intracellular to the extracellular region of muscle fibers (Mancini and Hunt, 2005).

Anthocyanins present in the Hi-A lamb diet did not alter the FA profile of the meat, which agreed with (Prommachart et al., 2021a). Conversely, Tian et al. (2022) observed that dietary anthocyanin decreased C18:0 and C12:0 SFA and some PUFA (C18:2n6 cis, C20:3n6, C20:4n6, C22:5n3, and C22:6n3). Later research suggested that anthocyanins can suppress oxidation resistance and enhance plasma superoxide dismutase resulting in a decline in SFA and an increase in PUFA levels because anthocyanins have hydroxyl groups in the aromatic ring, which can provide extra hydrogen or electron donors and eliminate excessive free radicals in the body. The concentration of anthocyanin in this research was similar to the average concentration tested by Prommachart et al. (2021a) but was up to 52% lower than that evaluated by Tian et al. (2021b) and influenced the resulting differences.

The five basic tastes that can be sensed on the tongue include sweet, sour, salty, bitter, and umami (Chandrashekar et al., 2006). In addition, as early as 1969, the role of smell in flavor was first described by studying nasal chemoreceptors (Mozell et al., 1969). While raw meat has only a salty, metallic, bloody taste, and sweet aroma (Wasserman, 1972), it is not until meat is cooked that 'meaty' aromas are noted (Macleod and Ames, 1986). Kerth and Miller (2015) described the development of these aromas in meat in lipid thermal degradation and Maillard reaction products. The breakdown of individual FA into short-chain compounds, such as aldehydes, acids, alcohols, and ketones, becomes volatile at normal cooking temperatures. Changes in FA composition due to species, muscle location, and diet (to name a few) cause changes in the composition of volatile compounds from changes in fatty acid chain length and the degree of saturation. Furthermore, Maillard reaction products are a result of the breakdown of peptides and result in individual amino acids reacting with local-reducing sugars (e.g. ribose from DNA and RNA). The primary elements in proteins, other than carbon, hydrogen, and oxygen, also found in the lipid fraction include nitrogen from the peptide backbone and sulfur from certain amino acid side chains. These lead to the production of numerous intermediates in the Maillard reaction, such as furans, pyrazines, pyrroles, oxazoles, thiophenes, thiazoles, and other heterocyclic compounds (Kerth and Miller, 2015).

Odor is one of the main contributors to meat flavor (Shahidi et al., 1986). While diet is a recognized factor needed to create the precursors to lamb meat flavor, it is not until the meat is exposed to heat that chemical reactions governed by temperature and the degree of moisture convert these precursors to flavor compounds such as the thermal breakdown of FA, Strecker aldehydes, and Maillard reaction products (Wasserman, 1979; Watkins et al., 2013). While a number of volatile aroma compounds are affected by diet, the trained sensory panel could not detect any major differences in taste. Nevertheless, 2-butanone and 2,3-butanedione, which are ketones produced from lipid degradation and the Maillard reaction perceived as fruity-green and buttery aroma (Kerth and Miller, 2015), respectively, were more abundant in the meat of lambs fed BGH than corn cob diets regardless of the variety. Ketones such as some monocarbonyls isolated from beef and mutton were associated with undesirable flavors (Hoffmann and Meijboom, 1968; Shahidi et al., 1986). The 2-butanone identified in lamb meat was positively correlated (r^2 = 0.83) with the livery flavor (Insausti et al., 2021). In addition, 2-propanone, which is a lipid degradation product perceived as a pungent aroma (Kerth and Miller, 2015), was also greater in chops from lambs fed BGH compared to corn cob diets. The 2-propanone is frequently reported as a volatile compound in meat with a low detection threshold associated with bloody and livery aftertaste flavors (Insausti et al., 2021).

The 3-methylbutanal and methylbenzene, which are Strecker aldehydes perceived as malty and sweet aromas, respectively (Kerth and Miller, 2015), were lower in chops from lambs fed Hi-A compared to BGH or Low-A diets. Certain aldehydes have been used as an index of the degree of off-flavor development because they are largely responsible for a wide range of oxidized flavors (Shahidi et al., 1986).

Several papers have discussed the role of FA in ruminant meat aroma and flavor development (Watkins et al., 2013; Arshad et al., 2018; Insausti et al., 2021). However, although no differences in the FA profile were found in the meat from lambs fed experimental diets, aromas were significantly altered, which may be related to the anthocyanin concentration (Luo et al., 2019; Prommachart et al., 2021a; Tian et al., 2021b). The antioxidant properties (antioxidant enzymes and compounds) in the meat of lambs fed anthocyanins may reduce the generation of free radicals and inhibit lipid peroxidation and some aromatic molecules that cause off-flavors derived from FA, which improves meat quality (Luo et al., 2019). Similarly, adding anthocyanins to goat (Tian et al., 2021b) and cattle (Prommachart et al., 2021a) diets improved the antioxidant capacity of muscle and suppressed the excessive oxidation of lipids, which reduced the generation of off-flavors and enriched the types of flavor substances. This was probably due to alterations in plasma lipid metabolism that modulates the formation of flavor compounds. In turn,

it may be related to regulating the expression of apoptosis-associated proteins and antioxidative enzymes by nuclear factor erythroid 2-related Factor 2 (Tan et al., 2019).

CONCLUSIONS

Utilization of Hi-A corn cobs as roughage in feedlot lamb diets maintained an unaltered intake, growth performance, most carcass traits and meat color parameters, the meat fatty acid profile, and sensory panel traits compared to regular corn cobs or bermudagrass hay. However, it positively influenced volatile aroma compounds of lamb chops. Therefore, utilization of this crop by-product in small ruminant diets may be advantageous for both the corn and sheep industries. Feeding lambs a diet containing 20% Hi-A corn cobs was not enough to change the oxidative discoloration of the meat during retail display, which suggests that additional research should test greater proportions of the Hi-A corn cob in the diets. Feeding Hi-A corn cobs for longer periods may result in important health benefits, which could be addressed in future investigations.

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Conflict of interest statement

The authors declare no conflict of interest.

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