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Effects of copper levels on goat carcass traits and meat quality

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ABSTRACT

The objective of the current study was to evaluate high levels of dietary copper (Cu) on goat carcass traits and meat quality. Thirty-six French Alpine goats (18.43 ± 2.35 kg) were randomly assigned to 6 treatments (basal diet with Cu levels at 0, 10, 20, 40, 80, and 160 ppm) with 6 replications each. The experiment was carried out for 102 d. Plasma Cu and enzymes, and slaughter variables were not different ($P > 0.05$) between Cu levels. Cu in the goat diets was significant ($P < 0.05$) for meat lightness (L*) and yellowness (b*); L* values were higher ($P < 0.05$) at 20 ppm and lower ($P < 0.05$) at 10 and 80 ppm; b* was highest ($P < 0.05$) for the 160 ppm level and lowest ($P < 0.05$) for 40 ppm. Meat adhesiveness presented differences ($P < 0.05$) between Cu levels; the 10 ppm group showed the highest value ($P < 0.05$) and 0 ppm the lowest value ($P < 0.05$). Meat juiciness for 10 ppm was higher ($P < 0.05$) than meat for the 80 ppm group. Linear regression demonstrated that b* and springiness were dependent ($\beta_1 \neq 0$; $P \leq 0.05$) on Cu levels in the diet. In conclusion, high Cu levels are recommended in the goat diet to enhance meat quality without affecting slaughter variables.

1. Introduction

The quality and quantity of goat meat depend upon production and husbandry practices (McMillin, 2010). México has 8.79 million goats and with a production yield of 39,937 tons of goat meat (FAO, 2021), from semi-extensive production systems with minimal resources (Silva-Jarquin et al., 2019), with seasonal cycles of goat meat and milk, and the breeding season can be induced by exposure of females to sexually active bucks (Carrillo et al., 2011). The Alpine breed comes from Switzerland and are excellent milkers. This French Alpine breed is descended from Swiss Alpine goats from the Alps, and has uniformity, large size, and high milk production, the males have long hairs along the spine, and adult bucks weigh about 77 kg with a height of 85−100 cm at the withers (Gurung and Solaiman, 2010). In Mexico, the Alpine breed was introduced from Europe and the USA to start breeding programs to improve milk production (Montaldo et al., 2010).

The growth and development of goats vary with genetics, breed, sex, nutrition, growth-promoting agents, and climate (McMillin, 2010). Copper (Cu) requirements for goats are a mínimum of 25 ppm and 40 ppm at maximum (NRC, 2007). According to Solaiman et al. (2001), goats can safely consume Cu levels from 50 to 300 ppm, while levels at 600 and 1,200 ppm elicit toxic effects. Cu effects on beef performance, lipid metabolism, and carcass and meat traits have been studied extensively (Engle, 2011; Cabrera et al., 2010; Ahola et al., 2005; Engle and Spears, 2000; Ward et al., 1991). However, Cu effects on performance and meat quality of goats have received comparatively little attention (Solaiman et al., 2006a, 2006b, 2007; Huang et al., 2013, 2014). Particularly, some studies have evaluated different Cu levels in the diet on performance and carcass traits of goat kids. Solaiman et al. (2006a, b) examined the effects of 0, 100, and 200 ppm of Cu sulfate, placed in capsules and inserted into the esophagus of Boer × Spanish goat kids, on lipid profiles, carcass traits, and carcass composition. Additionally, Huang et al. (2013, 2014) used 0, 20, 40, 80, 160, 320, and 640 ppm of Cu in pelleted rations to study effects on performance, carcass characteristics, and muscle fatty acid composition in Jianyang big-eared meat goats. Moreover, Solaiman et al. (2006a) reported that Cu decreased fat content in the twelfth rib of goats. However, Huang et al. (2014) found that high concentrations of Cu increased the fat content in the twelfth rib. These contrasting results indicate that decreased or increased Cu levels in goat diets could affect carcass traits and meat quality. Hence,

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the current study was carried out to evaluate the effects of Cu levels in the goat diet on slaughter variables and meat quality.

2. Materials and methods

The study was carried out at the facilities of MNA de México S.A. de C.V., Juárez, Nuevo León, México, located between 300 and 1,700 m above sea level, at 25 ° 31' and 25 ° 42' N and 99 ° 59' and 100 ° 14' W, with a temperature range 20–24 °C, annual precipitation between 600 and 900 mm, and is in a subtropic, arid climate (INEGI, 2021). The experiment was conducted according to the Official Mexican Standard (OMS) NOM-062-ZOO (1999), for humane care and welfare of experimental animals.

2.1. Animals, diets and experimental design

Thirty-six 3-month-old French Alpine kid male goats were chosen from single calvings with a mean body weight of 18.43 ± 2.35 kg (P = 0.9005). Goats were randomly assigned to six treatments (basal diet with Cu levels at 0, 10, 20, 40, 80, and 160 ppm) and were allocated to individual cages (80 × 60 × 100 cm) with a feeder and a drinker. An isonitrogenous and isocaloric diet (Table 1) was formulated according to NRC (2007). The diet was offered in pellet form, and prepared as follows: ingredients were ground to a powder, which was compacted using a perforated roller and treated with steam heat (85 °C, 17.0 % moisture) for 30–45 s. The Cu was added to the powdered diet during the pelleting process. Beginning on d 1, the goats were fed *ad libitum* offering the diet with different levels of copper, respectively, two times a day (at 900 h and 1600 h).

2.2. Analysis of plasma Cu and enzymes

Blood samples were collected by jugular venipuncture at 102 d to evaluate plasma Cu and enzymes. Blood samples were collected into 6-mL vacutainer tubes (Becton Dickinson, Vacutainer System, Franklin Lake, NJ, USA). Plasma preparation was carried out by centrifugation of whole blood at 1000 × *g* and plasma samples were stored at - 20 °C. Cu concentrations were measured by diluting plasma 1:4 in deionized water and using an optical emission spectrometer (Optima 2000 DV, Perkin-Elmer, Norwalk, CT, USA). Serum enzyme concentrations of glutamic oxaloacetic transaminase (GOT) and lactate dehydrogenase (LDH) were determined using a clinical blood chemistry analyzer (Synchron CX9 ALX, Beckman Coulter, Inc., Brea, CA, USA).

2.3. Slaughter variables and primal cut yields

At 102 d, goats were transported to the slaughter area according to the OMS NOM-051-ZOO (1995) and slaughter was carried out according to the OMS NOM-033-SAG/ZOO (2014). Slaughter was conducted on two days, where half of the animals per treatment (n = 3/treatment/-block; n = 18/block) were slaughtered each day; each slaughter day was considered as a block in the statistical model for data analysis. Slaughter weight (SW), and hot (HCW) and cold (CCW) carcass weights were recorded to calculate hot (HCY; (HCW/SW) × 100) and cold (CCY; (CCW/SW) × 100; stored at 4 ± 1.0 °C for 24 h *post-mortem*) carcass yields. Carcass pieces weights were recorded to calculate the percentage yield (Y; %) where percentage piece yield = (piece weight/SW) × 100) for front legs (FLY), rear legs (RLY), loin (LnY), rib (RY), neck (NY), kidney-pelvis-heart fat (KPHFY), and subcutaneous fat (SFY) yields.

2.4. Meat sampling and physicochemical analysis

The longissimus lumborum was selected for analysis of meat characteristics. Meat pH, color, water holding capacity (WHC), cooking loss (CL), and texture were measured on the right half of the carcass between the 7th and 12th ribs. Back fat thickness was recorded at the 12th and 13th ribs. Sensory evaluations were conducted at 12 h *post-mortem* using meat from the left half of the carcass between the 9th and 12th ribs. Physicochemical analysis were measured in duplicate per each sample per treatment (n = 12; 2 values/meat sample/treatment). Meat pH values were determinated with a puncture electrode (HI99163, Hanna Instruments WoonSocket, RI, USA). Color variables were measured on the meat surface with a colorimeter (CR-400; Konica Minolta®; Tokyo, Japan; CIE Standard Illuminant/Observer, D65/10). Meat color values for lightness (L*), redness (a*), yellowness (b*), Chroma (saturation index), and Hue angle (tonality) were recorded. WHC was evaluated by the compression method according to Tsai and Ockerman (1981) with slight modifications; this variable was calculated based on the difference in weight before and after pressure was applied, and was expressed as a percentage (Aquino-López et al., 2020). Cooking loss (CL) was determinated according to De Brito et al. (2016) with some modifications; meat samples were vacuum-packed individually in shrink vacuum bags

Table 1
Diet formulations and copper treatments.

Ingredients (%)[1]	Copper level (ppm)					
	0	10	20	40	80	160
Corn	40.50	40.50	40.50	40.50	40.50	40.50
Soy husk	32.00	32.00	32.00	32.00	32.00	32.00
Wheat bran	12.00	12.00	12.00	12.00	12.00	12.00
Soybean meal	10.00	10.00	10.00	10.00	10.00	10.00
Molasses	3.00	3.00	3.00	3.00	3.00	3.00
Vitamins and mineral premix	2.50	2.50	2.50	2.50	2.50	2.50
Chemical analysis (%; dry-matter basis)						
Ash	5.14	4.89	5.18	5.05	5.46	5.11
Crude protein	16.04	16.40	15.30	16.57	16.66	15.28
Ether extract	3.02	2.88	3.56	2.67	2.65	3.35
NDF	25.80	22.34	26.68	23.99	22.75	28.23
NFE	50.00	53.50	49.28	51.73	47.47	48.03
Minerals (ppm)						
Zn	76.22	127.60	133.90	120.20	107.50	119.20
Mn	32.27	39.90	37.50	32.70	33.70	33.90
Fe	309.90	198.40	229.40	207.00	240.00	226.80
S	1739.50	1721.00	2358.00	2080.00	1884.00	2577.00
Cu	12.76	15.07	24.00	50.20	100.70	167.90
Mo	0.29	4.90	1.00	4.70	5.20	2.80

[1] NDF - neutral detergent fiber, NFE - nitrogen-free extract, Zn - Zinc, Mn - manganese, Fe - iron, S - sulfur, Cu - copper, Mo - molybdenum.

and cooked at 75.0 ± 0.1 °C for 1 h by immersion in hot water; samples were cooled at room temperature (22 °C) for 20 min and removed from the bags, drained and weighed; the raw and cooked weights of each sample were recorded to evaluate the percentage CL (% CL = ([raw weight piece - cooked weight piece]/raw weight piece) × 100) (Hernández-Martínez et al., 2018).

2.5. Meat texture analysis

Shear force (SFc) and textural profile analyses of longissimus lumborum muscle were evaluated with a TA.XT2i texturometer (Stable Micro Systems, Surrey, England) with 12 samples per treatment (2 measurements/meat sample/treatment). Meat samples were cooked using the CL method, as sited above. SFc was measured using a Warner-Bratzler shear blade with a triangular slot cutting edge. Meat slices (2.5 cm long × 1.0 cm wide × 1.0 cm high), cut in parallel to the direction of the muscle fibres, were prepared to evaluate SFc. The parameters used in the texturometer were velocities of 2 mm/s pre-test, 2 mm/s during the test, and 10 mm/s post-test, and a distance of 1.5 mm. The SFc value (Newton; N) was the maximum point on the time-force curve obtained from the test. Meat textural analysis was carried out in standardized cylinders of 1.5 cm high and 1.5 cm diameter oriented perpendicular to the direction of the muscle fibres. A cylindrical piston was used to compress the sample during 2 test cycles, compressing the sample up to 60 % from the original height within a time span of 5 s between cycles, and time-force curves of deformation were obtained from the conditions (pre-test 1.0 mm/s, during the test 5.0 mm/s, and post-test 5.0 mm/s) established in the texturometer (Hernández-Martínez et al., 2018). The variables obtained were hardness (N), adhesiveness (g/s), springiness (mm), cohesiveness (dimensionless), gumminess (g), chewiness (g/mm), and resilience (dimensionless) (Bourne, 2002).

2.6. Meat sensory analysis

An affective sensory test was made by 50 panelists who eat meat frequently. Goat meat was vacuum-packed and cooked by immersion in water at 75.0 ± 0.1 °C for 1 h, and the samples were cooled by immersion in water at 4 °C for 10 min and stored at 4 °C for 24 h. Each panelist evaluated 5.0 g (1.0-cm cut cubes) of meat samples placed in plastic cups encoded with three numbers chosen at random. The sensory test was performed in the Universidad Autónoma de Nuevo León Sensory Laboratory outfitted with individual booths with a sink, table, and chair in each (Cantú-Valdéz et al., 2020). Odor, taste, juiciness, softness, and overall aceptabillity were evaluated with a 5-point hedonic scale (5 = liked much and 1 = disliked much) (Meilgaard et al., 2006).

2.7. Statistical analysis

Plasma Cu and enzymes, slaughter variables, pieces, and meat quality data were analyzed with general linear model (PROC GLM) and linear regression model (PROC REG) (SAS, 2006) to evaluate the copper level effect ($P \leq 0.05$). The GLM statistical model was $y_{ij} = \mu + T_i + ßj + \varepsilon_{ij}$; where y_{ij}: slaughter variables, pieces and meat quality, μ = global mean, T_i = treatment effect, ßj = block effect (1 and 2 d of slaughter), and ε_{ij} = experimental error ($N \sim (\mu, \sigma^2)$); sensory evaluation data considered the consumer effect as block. The H_0 reject was decided at $P \leq 0.05$ and Tukey test was carried out for means comparison (SAS, 2006).

The analysis of variance obtained with the linear regression (REG) procedure considered the independent variable effect (Cu levels) on dependent variables (slaugther, pieces, physicochemical, textura, and sensory traits) (SAS, 2006) and with the following statistical model (Montgomery, 2013): $y_i = \beta_0 + \beta_1 X_1 + \varepsilon_i$; where y_i = dependent or response variable, β_0 = the x-axis intercept when $X = 0$, β_1 = linear regression coefficient, which indicates the change in y, when the value of X increased by one unit, X_1 = independent variable (Cu levels), and ε_i = random error; this analysis evaluated the Cu level effect ($\beta_1 \neq 0$; $P \leq 0.05$) in diets on the response variables. Additionally, a second-order analysis ($\beta_{11} X_1^2$; cuadratic effect) was carried out, but P-values were not significant for all dependent variables, and the coefficient of determination (R^2) was lower than R^2 for the linear regression; hence, the results of the second-order fits were not reported.

3. Results

3.1. Plasma Cu and enzymes

Linear and quadratic analyses of Cu concentration showed no affect ($P > 0.05$) when Cu was sepplemented over 102 d. The mean plasma Cu concentration for all treatments was 2.99 ± 0.44 ppm. Similar treatment effects ($P > 0.05$) were seen after linear and quadratic analyses of GOT and LDH enzymes. The GOT mean value was 30.73 ± 4.52 U/L, and the LDH mean value was 133.04 ± 2.54 U/L for all treatments.

3.2. Slaughter variables and primal cut yields

Slaughter variables were not different ($P > 0.05$) between experimental groups (Table 2). Even so, Cu at 40 ppm in the diets presented high ($P > 0.05$) values for SW and 10 ppm gave high values for HCY, CCY, FLY, RLY, and LnY. High values ($P > 0.05$) were seen for KPHFY with 0 and 80 ppm, and the 0 ppm control group gaving high ($P > 0.05$) values for SFY. In contrast, values for Cu at 20 ppm were low ($P > 0.05$) for SW, HCY, and LnY, while 80 ppm presented the lowest ($P > 0.05$) values for legs (FLY, RLY). A linear regression analysis of slaughter variables and piece yields revealed no statistical correlations ($P > 0.05$; $\beta_1 = 0$) for Cu levels (X) as shown in Table 3.

3.3. Meat physicochemical analysis

Meat physicochemical variables for goats supplemented with Cu levels are given in Table 4. The Cu levels did not show significant differences ($P < 0.05$) for pH, WHC, a*, Chroma, and CL. Cu in the goat diets was significant ($P < 0.05$) for L* and b*; values for L* were higher ($P < 0.05$) at 20, 40, and 160 ppm and lower ($P < 0.05$) at 10 and 80 ppm. Additionally, b* was highest ($P < 0.05$) for 160 ppm and lowest ($P < 0.05$) for 40 ppm. Hue was not different ($P = 0.078$) between treatments, but with 160 ppm giving the high value. Regression analysis showed correlation effects ($P < 0.05$) for b* and Hue angle (tonality) due to Cu levels (Table 5).

3.4. Meat texture analysis

As shown in Table 6, adhesiveness presented differences ($P < 0.05$) between Cu levels, with the 10 ppm group showing the highest value and 0 ppm the lowest ($P < 0.05$) value. Resilience was not different ($P = 0.0639$) between experimental groups; despite 40 and 80 ppm exhibiting relatively high values and 0, 10, and 20 ppm low values. Shear force, hardness, springiness, cohesiveness, gumminess, and chewiness did not show differences ($P < 0.05$) between experimental groups; however, SFc was relatively high for 40 ppm and low for 80 ppm, while hardness was high for 0 ppm and low for 40 ppm. Only springiness presented correlations ($P < 0.05$) with respect to Cu levels (Table 7).

3.5. Meat sensory analysis

Sensory evaluations of meat from goats supplemented with copper levels in diets are shown in Table 8. Juiciness presented significant effect ($P < 0.05$) by treatments; this attribute presented more juiciness for 10 ppm goat meat than meat from the 0, 20, and 80 ppm. Odor, taste, softness, and overall aceptabillity were not different ($P < 0.05$) between treatments. Additionally, regression results for sensory attributes

Table 2
Effect of copper levels supplemented in goat diets on slaughter and piece yield variables.

Variable[1]	Copper levels (ppm)						SEM[2]	P-value
	0	10	20	40	80	160		
SW (kg)	38.60[3]	37.50	36.00	39.60	37.40	36.30	1.77	0.7441
HCY (%)	48.20	48.90	45.70	48.20	47.60	48.20	0.96	0.3813
CCY (%)	46.80	47.20	45.00	46.50	46.10	46.30	0.84	0.6362
FLY (%)	13.20	13.20	13.00	13.40	13.00	13.00	0.31	0.9359
RLY (%)	9.80	10.10	9.41	9.73	9.40	10.10	0.25	0.3181
LnY (%)	9.35	9.82	8.52	9.36	9.23	9.34	0.29	0.0816
RY (%)	9.96	10.00	9.78	10.20	10.3	9.59	0.39	0.4913
NY (%)	4.44	4.16	4.16	4.04	4.03	4.20	0.19	0.5573
KPHFY (%)	0.71	0.60	0.52	0.57	0.72	0.58	0.10	0.7481
SFY (%)	0.43	0.27	0.30	0.31	0.26	0.22	0.07	0.2754

[1] SW - slaughter weight, HCY - hot carcass yield, CCY - cold carcass yield, FLY - front legs yield, RLY - rear legs yield, LnY - loin yield, RY - rib yield, NY - neck yield, KPHFY - kidney-pelvis-heart fat yield, SFY - subcutaneous fat yield.
[2] SEM - standard error of the mean.
[3] Mean values, n = 6/treatment.

Table 3
Regression analysis of slaughter and yield variables of goats supplemented with different levels of copper in the diets.

Variables[1]	Coefficients[2]			MSE[3]	P-value
	®$_0$	®$_1$	R^2		
SW (kg)	37.90	−0.0047	0.0163	19.73	0.7692
HCY (%)	48.00	−0.0215	0.0266	5.10	0.6493
CCY (%)	46.60	−0.0195	0.0231	3.61	0.6877
FLY (%)	13.10	−0.0011	0.0054	0.49	0.9177
RLY (%)	9.87	−0.0101	0.0898	0.37	0.2217
LnY (%)	9.48	−0.0124	0.0429	0.80	0.4961
RY (%)	9.76	0.0141	0.0703	0.87	0.3115
NY (%)	4.36	−0.0088	0.0798	0.21	0.2643
KPHFY (%)	0.62	0.0001	0.0016	0.05	0.9739
SFY (%)	0.37	−0.0029	0.1181	0.03	0.1340

[1] SW - slaughter weight, HCY - hot carcass yield, CCY - cold carcass yield, FLY - front legs yield, RLY - rear legs yield, LnY - loin yield, RY - rib yield, NY - neck yield, KPHFY - kidney-pelvis-heart fat yield, SFY - subcutaneous fat yield.
[2] β_0 – the x-axis intercept when $X = 0$, β_1 - linear regression coefficient, which indicates changes in y when the value of X is increased by one unit; R^2 - the coefficient of determination.
[3] MSE - mean square of error.

evaluation in goat meat showed no correlations ($P < 0.05$; Table 9) for Cu levels supplemented in the diets.

4. Discussion

4.1. Plasma Cu and enzymes

The results obtained in the current study indicated that Cu levels in diets did not affect plasma Cu and enzymes. Plasma Cu content in the current study gave values near to those of Solaiman et al. (2001), who supplemented 1,200 mg of Cu/kg of diet per head per day. Those authors indicated that plasma Cu was independent of Cu supplementation except at very high levels (> 600 mg of Cu/kg of diet per head per day). Differences in individual animal responses to higher Cu dosages also contributed to high variation in GOT values and elevated levels of GOT were associated with apparent clinical signs of Cu toxicosis (Solaiman et al., 2001; Zhang et al., 2012). In the current study, GOT values were lower than in the study of Solaiman et al. (2001); hence, goats did not have clinical signs of Cu toxicosis for this study with 10, 20, 40, 80, and 160 ppm of Cu in diets. This result can be supported according findings

Table 5
Regression analysis on meat quality for goats supplemented with different levels of copper in the diets.

Variable[1]	Coefficients[2]			MSE[3]	P-value
	β_0	β_1	R^2		
pH	6.39	−0.0007	0.0114	0.15	0.3713
WHC (%)	75.30	−0.0014	0.0002	35.87	0.9120
L*	36.20	0.0029	0.0074	3.69	0.4717
a*	19.10	0.0048	0.0336	2.28	0.1232
b*	2.93	0.0042	0.0904	0.59	0.0103
Chroma	19.50	0.0040	0.0438	1.17	0.0777
Hue	9.05	0.0076	0.0526	3.54	0.0526
CL (%)	20.70	0.0022	0.0008	20.51	0.8660

[1] WHC - water holding capacity, L* - lightness, a* - redness, b* - yellowness, Chroma - saturation index, Hue - Hue angle (tonality), CL - cooking loss.
[2] β_0 - the x-axis intercept when $X = 0$, β_1 - linear regression coefficient, which indicates changes in y when the value of X is increased by one unit; R^2 - the coefficient of determination.
[3] MSE - mean square of error.

Table 4
Goat meat (longissimus lumborum) quality for goats supplemented with different levels of copper in the diets.

Variable[1]	Copper levels (ppm)						SEM[2]	P-value
	0	10	20	40	80	160		
pH	6.43	6.52	6.13	6.32	6.40	6.28	0.10	0.2133
WHC (%)	76.40	72.80	75.10	76.10	76.40	74.50	1.77	0.6746
L*	35.90^{ab}	35.60^{b}	37.90^{a}	36.40^{a}	35.60^{b}	36.90^{a}	0.53	0.0313
a*	19.10	19.50	18.80	19.10	19.30	20.00	0.45	0.4649
b*	2.92^{ab}	3.05^{ab}	3.40^{ab}	2.67^{b}	3.19^{ab}	3.68^{a}	0.22	0.0238
Chroma	19.40	19.80	20.00	19.40	19.40	20.30	0.31	0.1275
Hue	8.64	9.89	9.80	8.55	9.38	10.48	0.54	0.0783
CL (%)	22.10	20.30	19.50	21.4	19.50	21.50	1.96	0.9215

[a-b]Means (n = 12; 2 values/meat sample (goat)/treatment) in rows and with different superscripts are significantly different ($P < 0.05$).
[1] WHC - water holding capacity, L* - lightness, a*: redness, b* - yellowness, Chroma - saturation index, Hue - Hue angle (tonality), CL - cooking loss.
[2] SEM - standard error of the mean.

Table 6
Texture analysis of goat meat (longissimus lumborum) supplemented with different levels of copper in the diets.

Variable[1]	Copper levels (ppm)						SEM[2]	P-value
	0	10	20	40	80	160		
SFc (N)	24.2	17.0	21.3	25.70	20.18	25.10	2.60	0.1624
Hardness (N)	20.70	14.97	15.76	16.84	16.94	14.06	2.14	0.1522
Adhesiveness (g/s)	−6.33[b]	−0.32[a]	−0.50[a]	−0.52[a]	−1.22[a]	−1.41[a]	0.78	0.0001
Springiness (mm)	0.50	0.50	0.49	0.52	0.52	0.54	0.01	0.1158
Cohesiveness	0.59	0.57	0.58	0.60	0.61	0.60	0.01	0.3012
Gumminess (g)	15.5	9.60	10.30	9.51	10.2	9.35	1.75	0.1197
Chewiness (g/mm)	7.75	5.04	5.17	5.05	5.29	5.10	0.96	0.1520
Resilience	0.26	0.26	0.26	0.29	0.29	0.27	0.01	0.0639

[a-b]Means (n = 12; 2 values/meat sample (goat)/treatment) in rows and with different superscripts are significantly different (P < 0.05).
[1] SFc - shear force.
[2] SEM - standard error of the mean.

Table 7
Regression analysis of texture variables of goat meat (longissimus lumborum) supplemented with different levels of copper in the diets.

Variable	Coefficients[1]			MSE[2]	P-value
	β_0	β_1	R^2		
Shear force (N)	21.43	0.0192	0.0205	7.29	0.3321
Hardness (N)	20.25	−0.0488	0.0524	6.64	0.1399
Adhesiveness (g/s)	−1.78	0.0044	0.0087	7.03	0.5509
Springiness (mm)	0.50	0.0003	0.0912	0.00	0.0490
Cohesiveness	0.58	0.0002	0.0456	0.00	0.1693
Gumminess (g)	11.69	−0.0235	0.0392	4.08	0.2030
Chewiness (g/mm)	6.03	−0.0104	0.0260	2.22	0.3019
Resilience	0.27	0.0001	0.0105	0.00	0.5129

[1] β_0 - the x-axis intercept when $X = 0$, β_1 - linear regression coefficient, which indicates the change in y, when the value of X is increased by one unit; R^2 - the coefficient of determination.
[2] MSE - mean square of error.

by Shen et al. (2021) in which LDH was released during immune response by leucocytes, and an increased serum LDH suggested that muscle, liver, and kidney cells may be damaged. In the current study, GOT and LDH were not affected, hence goat health status can be considered as stable.

4.2. Slaughter variables and primal cut yields

Results of slaughter variables were similar to those reported by Huang et al. (2013) and Solaiman et al. (2006a, b) for goats and Cheng et al. (2008) for sheep. Those authors used high levels of Cu and indicated that diet formulation, copper administration method, and sex contributed to carcass traits. Results from the current study contribute the evaluation of previously unexamined dietary Cu levels of 10 and 40 ppm and their effects on goat piece yields; particularly for primal cut yields which have received limited study. Although, the results of linear regression analyses indicated that slaughter variables and piece yields did not correlate with incremental changes in Cu levels.

4.3. Meat physicochemical analysis

Huang et al. (2014) did not find effects on pH and WHC when evaluating Cu levels less than 320 ppm. In contrast, pH values from the current study with 10–160 ppm of Cu gave high values, likely due to glycolytic metabolites in the muscle *peri-mortem* (Kannan et al., 2003; Simela et al., 2004a, b; Webb et al., 2005), as a consequence of the nervous nature of goats and goats being highly prone to stress (Webb et al., 2005).

In contrasts to findings in the current study, Cu supplementation (0, 20, 40, 80, 160, 320, and 640 mg/kg) tended to decrease L* values but did not affect a* and b* values of goat meat (Huang et al., 2014). Results for b* (significant) and a* (not significant) in the current study, when Cu levels were supplemented at 10, 20, 40, 80, and 160 ppm, indicated that Cu could modify meat yelloness without affecting the meat redness due to the conversion of oxymyoglobin to metmyoglobin, which results from a decrease in heme redox stability rather than the oxidation of specific amino acid residues (Faustman et al., 2010). Regression analyses indicated that high levels of Cu supplementation increased L* and b* values. Other studies with high levels of Cu did not evalute Hue angle and Chroma (Solaiman et al., 2006a, b; Huang et al., 2013, 2014). However, results presented for Hue angle in the current study could indicate that

Table 9
Regression analysis of sensory evaluation of cooked goat meat (longissimus lumborum) supplemented with different levels of copper in the diets.

Variable	Coefficients[1]			MSE[2]	P-value
	β_0	β_1	R^2		
Odor	3.67	−0.0005	0.0012	0.60	0.5574
Taste	3.57	0.0007	0.0018	0.87	0.4609
Juiciness	3.52	−0.0004	0.0006	0.93	0.6763
Softness	4.07	−0.0013	0.0059	0.89	0.1884
Overall aceptabillity	3.74	−0.0006	0.0016	0.74	0.4964

[1] β_0 - the x-axis intercept when $X = 0$, β_1 - linear regression coefficient, which indicates the change in y, when the value of X is increased by one unit; R^2 - the coefficient of determination.
[2] MSE - mean square of error.

Table 8
Sensory evaluation of cooked meat (longissimus lumborum) from goats supplemented with different levels of copper in the diets.

Variable	Copper levels (ppm)						SEM[1]	P-value
	0	10	20	40	80	160		
Odor	3.78	3.70	3.48	3.64	3.66	3.60	0.09	0.3340
Taste	3.54	3.64	3.56	3.66	3.53	3.72	0.13	0.8715
Juiciness	3.39[b]	3.78[a]	3.36[b]	3.61[ab]	3.30[b]	3.50[ab]	0.12	0.0472
Softness	4.30	4.04	3.92	3.90	3.92	3.92	0.13	0.1799
Overall aceptabillity	3.80	3.78	3.66	3.72	3.60	3.68	0.12	0.8318

[a-b]Means (n = 50 consumers) in rows and with different superscripts are significantly different (P < 0.05).
[1] SEM - standard error of the mean.

copper affects meat tonality (Hue angle). Reagarding CL, goat studies have reported a CL of 35 % (Swan et al., 1998; Dhanda et al., 1999). CL obtained in the current study was lower than 35 % for the experimental groups when compared to the control group, which indicated that CL of the goat meat did not lose an excessive amount of water during the thermal process.

4.4. Meat texture analysis

The current study is the first to report the textural analysis of goat meat following Cu supplementation in the diet. The increased adhesiveness with Cu supplementation could be due to meat fat quantity as reported by Solaiman et al. (2006a, b) and Engle (2011); those authors indicated that high Cu levels in the diet resulted in low fat content. This effect could explain why the 10 ppm of Cu meat had high adhesion due to its low fat content. Similarly, results for resilience could be due to meat fat content where high levels of Cu resulted in low fat content (Solaiman et al., 2006a, b); hence, high resilience to deformation. In contrast to results in the current study, Huang et al. (2014) obtained SFc differences due to high levels of Cu in the diet when Cu concentrations were increased to 320 and 640 mg/kg.

4.5. Meat sensory analysis

The meat fat content is related to texture and sensory traits. Juiciness effects obtained in the current study could be due to fat content being perceived as juiciness by the test panel. As suggested by Cross et al. (1986) and Webb et al. (2005), juiciness perception is related to intramuscular lipids and moisture content of meat. Furthermore, Xiong et al. (2014) indicated that low intramuscular fat content gave cooked product less taste and juiciness. Additionally, water introduced into products contributes to meat juiciness (Webb et al., 2005). Overall acceptability obtained in the current study was similar to that of Sen et al. (2004) who did not find differences in sensory variables. Regression analysis of sensory attributes in the current study indicated that there was no correlation between sensory data and Cu levels.

5. Conclusion

High copper high levels in the goat diet affected meat quality and did not affect slaughter variables. Cu at 20 ppm improved meat lightness and 160 ppm of Cu improved yellowness. Hue characteristics also improved when Cu levels were increased in the diets. Cu in the goat diets had effect for adhesiveness with 10 ppm having the highest effect. An analysis of goat meat composition could be carried out in future studies to evaluate the potential relationships between dietary Cu supplementation with texture and meat sensory qualities.

Declaration of Competing Interest

The authors report no declarations of interest.

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