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Impact of dietary *Rhus coriaria* (Sumac) powder supplementation on meat quality, serum minerals, and intestinal histomorphology in Cobb-500 broiler chickens

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Abstract

Phytogenic feed additives are increasingly explored as antibiotic-free strategies to support broiler productivity, meat quality, and gut health. *Rhus coriaria* L. (sumac) is a polyphenol-rich spice with reported antioxidant, antimicrobial and anti-inflammatory activity, but the dose-dependent effects on carcass meat quality, serum macro-minerals and intestinal architecture in modern broilers remain incompletely characterized. This study evaluated the effect of graded dietary levels of sumac powder on breast and thigh meat quality, serum calcium and phosphorus, and duodenal and jejunal histomorphology of Cobb-500 broilers. Three hundred one-day-old Cobb-500 broiler chicks were assigned to five dietary treatments (0, 1, 2, 3 or 4 g sumac/kg feed; 60 birds per treatment, distributed among four pens of 15 birds each) for 35 days, and outcomes were analyzed by one-way ANOVA. Meat-quality and serum parameters were assessed in three birds/treatment and histomorphological outcomes in five birds/treatment, with the individual bird as the experimental unit. Sumac did not affect breast-meat water-holding capacity, drip loss, cooking loss, pH or sensory scores ($P > 0.05$). Thigh cooking loss decreased from 26.4% in controls to 5.7% at 4 g/kg ($P = 0.001$), and breast-meat lipid oxidation (thiobarbituric acid-reactive substances) tended to be lowest at 1 g/kg (0.31 vs 0.41 mg malondialdehyde/kg in controls; $P = 0.058$). Serum phosphorus was highest at 2 g/kg (6.20 mg/dL; $P = 0.021$); calcium was unaffected ($P = 0.325$). In both the duodenum and jejunum, villus length, villus width, villus: crypt ratio and estimated villus surface-area index were significantly greater, and crypt depth significantly smaller, at 1–2 g/kg than in controls or at 3–4 g/kg ($P < 0.001$ for all); tunica muscularis thickness was unaffected. Dietary sumac powder produced outcome-specific responses in Cobb-500 broilers: thigh-meat cooking loss decreased progressively with increasing inclusion, with the greatest reduction at 4 g/kg; serum phosphorus concentration was highest at 2 g/kg; and duodenal and jejunal villus architecture was most favorably altered at 1–2 g/kg, with no further improvement at 3–4 g/kg. These findings suggest that 1–2 g/kg sumac may represent a suitable inclusion level for altering selected histomorphometric indices of intestinal architecture, whereas higher inclusion (up to 4 g/kg) may be preferable when improved cooking yield is the primary objective; however, the small per-treatment sample sizes for meat and serum traits (three birds/treatment) and the absence of a pre-specified sample-size calculation mean these findings should be confirmed in an adequately powered, independently replicated trial.

1. Introduction

Global demand for poultry meat continues to rise, as it represents an affordable, high-quality source of animal protein for a growing human population (Alexandratos and Bruinsma 2012; Mottet and Tempio 2017). To meet this demand, broiler production has moved toward increasingly intensive systems that historically relied on sub-therapeutic doses of antibiotics for growth promotion and disease control. The emergence of antimicrobial resistance and consumer pressure for residue-free animal products have led to bans or restrictions on antibiotic growth promoters in many, though not all, countries and production systems, and to an urgent search for safe, effective and sustainable alternatives (Diaz-Sanchez et al. 2015; Yang et al. 2015). Among these alternatives, phytogenic feed additives, including plant-derived spices, herbs, extracts, and essential oils, have attracted considerable attention because of their broad spectrum of biological activities, favorable safety profile and consumer acceptance (Abd El-Hack et al. 2022; Alagawany et al. 2019). Whole-plant powders, however, are inherently more variable than purified extracts or essential oils, because their concentration of active constituents is lower and less standardized. Other classes of feed additives, including prebiotics, probiotics, enzymes, organic acids, microalgae and nanoparticles, have also been investigated to support poultry production and health; among these, phytogenic compounds have attracted particular attention because of their favorable safety profile (Abd El-Hack et al. 2018; Reda et al. 2025).

Rhus coriaria L. (sumac), a member of the family Anacardiaceae that is widely distributed across the Mediterranean basin, the Middle East and parts of North America, is one of the most extensively studied phytogenic candidates for poultry nutrition (Abu-Reidah et al. 2015; Alsamri et al. 2021). The dried, ground drupes of sumac have been used for centuries as a souring spice and as a traditional remedy for digestive, cardiovascular and inflammatory disorders (Alsamri et al. 2021). Phytochemical characterization by HPLC–DAD–ESI-MS/MS has identified more than 200 bioactive constituents in sumac, dominated by

hydrolysable tannins (mainly gallotannins), gallic and benzoic acids, flavonol glycosides (myricetin, quercetin, kaempferol), anthocyanins and organic acids such as malic and citric acids (Abu-Reidah et al. 2015; Sakhr and El Khatib 2020). The phytochemical profile summarized above has been reported for different plant fractions and preparations, including whole fruit, seed, and extracts. As detailed in the Materials and Methods, the commercial powder used in the present trial was not independently re-analyzed, so this composition should be regarded as representative rather than confirmed for the specific batch tested. Sumac fruits are also a source of tocopherols, ascorbic acid, unsaturated fatty acids (oleic and linoleic) and macro-minerals including calcium, phosphorus, potassium and magnesium (Matthaus and Özcan 2014; Zannou et al. 2024). This complex phytochemical profile underlies the documented antioxidant, antimicrobial, anti-inflammatory, hypolipidemic and hypoglycemic activities of *Rhus coriaria* (Alsamri et al. 2021; Batiha et al. 2022).

Recent studies in broilers, laying hens and quail have shown that dietary inclusion of sumac powder or extract can improve growth performance, feed efficiency, immune competence and antioxidant status while modulating serum lipid profile and gut microbiota composition (Ahmadian et al. 2020; Golzadeh et al. 2012; Mansoub 2011; Reda et al. 2024; Reda et al. 2026). Ahmadian et al. (2020) reported that supplementing Ross broilers with 1–3% sumac berries reduced abdominal fat by up to 62%, decreased serum LDL cholesterol and enhanced antibody titers against Newcastle disease and avian influenza vaccines. Reda et al. (2026) demonstrated that dietary sumac seed powder at 3 g/kg alleviated the negative effects of high stocking density on Arbor Acre broilers, improving live body weight, feed conversion ratio, enzymatic antioxidant capacity (SOD, CAT, GSH, TAC), immunoglobulin titers and the villus: crypt ratio, while reducing malondialdehyde and corticosterone concentrations. Kheiri et al. (2015) observed favorable changes in intestinal morphology and a shift of cecal microbiota from *Escherichia coli* toward *Lactobacillus* spp. in broilers fed low levels of sumac.

Villus length and width determine the mucosal surface area available for nutrient absorption, whereas crypt depth reflects the rate of epithelial cell turnover and the maintenance cost of the mucosa; a higher villus: crypt ratio is therefore generally interpreted as indicating a more mature, energetically efficient absorptive epithelium. Despite the promising findings summarized above, information on the effects of *Rhus coriaria* specifically on carcass and meat-quality attributes (water-holding capacity, drip and cooking losses, pH, lipid oxidation, and sensory characteristics), serum macro-mineral status, and the fine architecture of the duodenum and jejunum in modern high-performing Cobb-500 broilers is still fragmentary. Moreover, dose–response relationships have not been fully established. Although low dietary inclusion levels appear beneficial, excessive tannin intake from any dietary source can bind dietary proteins and minerals and potentially impair nutrient utilization (Huang et al. 2018). Because the tannin content of the specific sumac product used in this study was not independently assayed, the tannin-related interpretations should be presented as general hypothesis rather than a dose-specific explanations of the results. It was therefore hypothesized that graded dietary levels of *Rhus coriaria* powder (1–4 g/kg feed) would exert dose-dependent effects on meat quality, serum minerals, and intestinal histomorphology in Cobb-500 broilers, with the optimum inclusion level potentially varying across result domains (meat quality, serum minerals, and intestinal histomorphology) that could be identified experimentally for each. Accordingly, the present study was undertaken to evaluate these responses over a 35-day production cycle under standard commercial rearing conditions.

2. Materials and Methods

2.1 Ethical considerations

All animal-handling procedures adhered to internationally recognized ethical standards for the humane treatment of research animals and were conducted in accordance with the ARRIVE 2.0 guidelines. Prior ethical clearance was obtained from the Institutional Review Board and the Medical Ethics Committee of the Faculty of Veterinary Medicine, King Faisal University (No. KFU-344/2026). The experiment was carried out at the research facility of the Nutrition and Clinical Nutrition Department, Teaching Veterinary Hospital, Faculty of Veterinary Medicine, New Valley University, from 3 November to 11 December 2025.

2.2 Experimental birds, design and management

Three hundred (n = 300) one-day-old, unsexed Cobb-500 broiler chicks were obtained from a certified commercial hatchery. Chicks were individually weighed on arrival and randomly allocated to five dietary treatments of uniform mean initial body weight. A computer-generated random-number sequence and allocation was concealed until the birds were assigned to pens. The sequence was generated by a member of the research team who was not involved in subsequent outcome assessment, and pen location within the house was likewise randomized to avoid positional confounding. Each treatment comprised 60 birds distributed across four replicate floor pens of 15 birds per pen (completely randomized design). All chicks were visually inspected on arrival for uniformity and clinical health; none were excluded as runted, visibly diseased or injured before randomization. No mortality or culling was recorded in any of the treatment groups during the 35-day trial. Birds were housed in a curtain-sided, environmentally controlled house on clean wood-shaving litter. Ambient temperature was set at 33 ± 1 °C during the first week and gradually decreased by approximately 3 °C per week to a final temperature of 24 ± 1 °C at 35 days of age. Relative humidity was maintained between 55 and 65%. A lighting program of 23 h light:1 h dark was applied throughout the trial; light intensity was not recorded. Feed (in pellet form) and clean drinking water were supplied *ad libitum*. Standard vaccination and hygiene protocols recommended by the Cobb-500 management guide were followed.

2.3 Dietary treatments

A single corn–soybean basal diet was formulated to meet or exceed the nutrient requirements of Cobb-500 broilers as recommended in the Cobb500 Broiler Performance & Nutrition Supplement (Cobb-Vantress 2022) and National Research Council (1994). Two-phase feeding was applied: a starter diet from 1 to 21 days of age and a grower-finisher diet from 22 to 35 days. The composition and calculated chemical analysis of the basal diets are presented in Table 1. Dietary treatments were as follows:

T1 (control): basal diet without additive
T2: basal diet + 1 g sumac/kg feed
T3: basal diet + 2 g sumac/kg feed
T4: basal diet + 3 g sumac/kg feed
T5: basal diet + 4 g sumac/kg feed

Rhus coriaria powder was obtained from Biochem Egypt Limited (Hadayek El Ahram, Giza, Egypt) as a finely ground, food-grade product; the certificate of analysis, specific batch/lot number and storage conditions for this product during the trial are not available for citation here and should be confirmed by the corresponding author from supplier/laboratory records if required by the editor. Because inclusion levels were low (≤4 g/kg feed, i.e. ≤0.4% of the diet), sumac powder was added on top of the basal diet without substitution of another ingredient, and the same basal formulation (Table 1) was fed across all treatments; diets were therefore not independently re-balanced to remain isoenergetic and isonitrogenous beyond the small nutrient contribution of the additive itself. The sumac powder and the experimental diets were not independently analyzed in this trial for total phenolic content, hydrolysable tannins, moisture or proximate composition; the actual concentration of these presumed bioactive constituents in the test material was therefore not confirmed and is referenced from previously published phytochemical characterizations of *Rhus coriaria* (see Introduction). According to Abu-Reidah et al. (2015) sumac contains more than 200 bioactive compounds, including flavonol glycosides, phenolic acids, anthocyanins and hydrolysable tannins. The proximate composition of the basal diet was determined according to AOAC International (2007).

Table 1. Ingredients and nutrient composition of the basal diets

Ingredient	Starter (1-21 d)	Grower-finisher (22-35 d)
Ingredients		
Yellow corn	53.87	59.18
Soybean meal (44% CP)	36.00	30.01
Sunflower oil	2.60	5.10
Corn gluten meal	4.00	2.15
Dicalcium phosphate	0.83	0.82
Limestone, ground	1.84	1.64
L-Lysine·HCl	0.15	0.32
DL-Methionine	0.12	0.18
Vitamin–mineral premix[1]	0.30	0.30
Common salt	0.30	0.30
Total	100.00	100.00
Calculated chemical analysis[2,3]		
Crude protein (%)	23.08	20.02
Ether extract (%)	5.01	7.59
Crude fibre (%)	3.80	3.46
Calcium (%)	1.00	0.90
Available phosphorus (%)	0.42	0.41
Lysine (%)	1.30	1.30
Methionine (%)	0.50	0.50
Metabolisable energy (kcal/kg)	3001	3212

[1] Premix provided per kg of complete diet: vitamin A, 6 250 000 IU; vitamin D_3, 2 500 000 IU; vitamin E, 25 000 mg; vitamin K_3, 1 750 mg; vitamin B_1, 500 mg; vitamin B_2, 2 750 mg; vitamin B_6, 1 250 mg; vitamin B_{12}, 10 mg; nicotinic acid, 20 000 mg; calcium pantothenate, 500 mg; folic acid, 500 mg; biotin, 50 mg; iron, 22 g; copper, 2.5 g; zinc, 37.5 g; manganese, 31 g; iodine, 650 mg; selenium, 113 mg; cobalt, 50 mg.
[2] Crude protein, ether extract and crude fiber analyzed according to AOAC International (2007).
[3] Ca, available P, lysine, methionine and ME calculated according to National Research Council (1994).

2.4 Slaughter procedure and sample collection

On day 35, feed was withdrawn 8 h before slaughter while free access to water was maintained. Three birds per treatment, drawn from three of the four replicate pens per treatment, with body weight within ±10% of the treatment mean, were randomly selected from this eligible subset, weighed and slaughtered by severing the jugular vein and carotid artery according to the halal slaughter method. After 2 min of bleeding, carcasses were scalded in water at 63 °C for 120 s, mechanically plucked and manually eviscerated. Weights of the liver, spleen, heart and gizzard were recorded. Breast (*Pectoralis major*) and thigh (*Iliotibialis*) muscles were excised, placed in clean plastic trays and chilled at 4 °C overnight for subsequent physical, chemical and sensory analyses (Yitbarek et al. 2016). Blood samples (~5 mL/bird) were collected from the same three birds per treatment from the wing vein before slaughter into plain tubes, allowed to clot for 30 min and then centrifuged at 3000 rpm for 15 min at 4 °C. The sera were stored at -20 °C until further analysis. On the same day, five additional birds per treatment, distributed as evenly as possible across the four replicate pens per treatment (i.e., one or two birds per pen), were humanely euthanized by cervical dislocation for histomorphological analysis of the intestine.

2.5 Meat quality analyses

***Sample preparation*:** In the laboratory, breast and thigh muscles were separated and each cut into small pieces using a clean knife. One portion was reserved for chemical analysis and the remainder for sensory evaluation and physical measurements.

***pH determination*:** The pH of breast and thigh muscles was measured directly at 24 h postmortem, consistent with the timing used for drip-loss and cooking-loss assessment, using a portable pH meter fitted with a stainless-steel penetration probe (Hanna HI-99163 Foodcare pH meter, Hanna Instruments, Cluj-Napoca, Romania). The probe was inserted into the geometric center of each sample to a depth of at least 2 cm. Each sample was measured in triplicate; the meter was calibrated with pH 4.0 and 7.0 buffers before each session (Lin et al. 2022).

***Drip loss*:** For drip loss breast fillets and thigh samples were removed 24 h postmortem, weighed, stored in polyethylene trays covered with waterproof plastic film at 3 ± 1 °C for 72 h, then blotted and re-weighed, representing drip loss during the interval from 24 to 96 h postmortem (Dirinck et al. 1996; Northcutt et al. 1994).

$$\text{Drip loss (\%)} = [(\text{initial weight} - \text{final weight})/\text{initial weight}] \times 100$$

***Cooking loss*:** Cooking loss was determined on intact breast and thigh samples 24 h postmortem, in triplicate (three independent subsamples per bird, averaged within bird before analysis) (Honikel and Kim 1986). Samples were weighed, placed in heat-resistant polyethylene bags and cooked in a water bath maintained at 82–85 °C for 10 min, cooled to 40 °C and reweighed; the final internal temperature of the samples was not recorded.

$$\text{Cooking loss (\%)} = [(\text{fresh weight} - \text{cooked weight})/\text{fresh weight}] \times 100.$$

Water-holding capacity (WHC): WHC was determined by the filter-paper press method of (Biesek and Kuźniacka 2020). Approximately 0.300 ± 0.015 g of meat (W1) was placed between two Whatman No. 1 filter papers under a 2-kg load for 5 min and re-weighed (W2).

$$WHC\ (\%) = (W2 \times 100)/W1$$

where W1 is the sample weight before pressing and W2 the sample weight after pressing, such that higher values indicate greater water holding capacity.

Sensory evaluation: Sensory quality of breast and thigh meat was assessed by a panel of three trained members of the Food Hygiene, Safety and Technology Department (Meat Branch), Faculty of Veterinary Medicine, Assiut University, working under blinded conditions. This represented a small, semi-trained acceptability panel rather than either a fully trained descriptive sensory panel or a large consumer hedonic panel, and results should be interpreted accordingly. Samples were cooked in a water bath at 75 °C for 15 min, allowed to reach room temperature, randomly coded and presented in a monadic sequential order that was independently randomized for each panelist (Cason et al. 1997). All five treatment samples for a given cut (breast or thigh) were evaluated by each panelist within a single session. Panelists cleansed their palates with water between samples. Six attributes - odor, color, hardness (texture), juiciness (taste), appearance, and overall acceptability were scored on a 5-point hedonic scale (1 = dislike extremely, 5 = like extremely) (Mellen et al. 2014).

Thiobarbituric acid-reactive substances (TBARS): Lipid oxidation of breast and thigh meat was estimated by the thiobarbituric acid-reactive substances (TBARS) method (Radha Krishnan et al. 2014). Three grams of muscle were homogenized with 9 mL of distilled water for 2 min. One milliliter of the homogenate was mixed with 2 mL of trichloro acetic acid (TCA)/ thiobarbituric acid (TBA) reagent (150 g TCA and 2.88 g TBA in 1 L distilled water) and 50 µL of 10% butylated hydroxyanisole (BHA), vortexed, heated in a boiling water bath for 15 min, cooled for 10 min and centrifuged at 3000 rpm for 15 min at 4 °C. Absorbance of the supernatant was read at 531 nm on a Jenway 6850 spectrophotometer against a reagent blank. A standard curve was prepared with 1,1,3,3-tetraethoxypropane (TEP) at 0–50 µL of a 1×10^{-3} M standard solution (curve equation $y = 0.8132x + 0.0447$). Results were expressed as mg malondialdehyde (MDA) equivalents per kg of meat, corrected by a dilution factor of 4, and interpreted according to Egyptian Standard ES:63-10/2006 (Jehan and Asmaa 2025).

2.6 Serum mineral analysis

Serum calcium and phosphorus (mg/dL) were determined by colorimetric enzymatic assays using commercial diagnostic kits (Spectrum Diagnostics, Cairo, Egypt) on a Biochrom Libra S22 UV-Vis spectrophotometer (Biochrom Ltd., Cambridge, UK), following the manufacturer's instructions.

2.7 Intestinal histomorphology

Immediately after euthanasia, 2 cm segments of the mid-duodenum (descending loop) and mid-jejunum were excised, gently flushed with 0.9% saline to remove digesta and fixed in 10% neutral buffered formalin for 72 h. Fixed tissues were routinely processed (Elmeligy et al. 2024), dehydrated in a graded ethanol series, cleared in xylene and embedded in paraffin wax. Sections with a thickness of 5 µm were cut with a rotary microtome, mounted on glass slides and stained with hematoxylin and eosin (H&E). Slides were examined under a Leica DM 500 light microscope equipped with a calibrated digital camera and image-analysis software.

The following indices were measured on three well-oriented, finger-shaped villi and five crypts per cross-section, using three cross-sections per bird (Mahmoud et al. 2025):

Villus length, VL (µm)
Villus width, VW (µm)
Crypt depth, CD (µm)
Villus: crypt ratio (VL/CD)
Tunica muscularis thickness (µm)
Estimated villus surface-area index (µm²) = π × VW × VL
(assuming simplified cylindrical villus geometry)

2.8 Statistical analysis

The experiment followed a completely randomized design. Data were tested for normality using the Shapiro–Wilk test ($P > 0.05$) and analyzed using IBM SPSS Statistics v.23. The replicate pen was the experimental unit for performance-related traits, while the individual bird was the experimental unit for carcass, meat quality, serum and histomorphological parameters; this bird-level analysis of destructively sampled traits follows common practice in broiler nutrition trials but does not formally account for pen-level clustering, which is noted as a limitation below. Treatment effects were evaluated by one-way ANOVA. When a significant treatment effect was detected ($P < 0.05$), pairwise comparisons were done using Fisher's LSD test. When an outcome showed zero variance across all treatments, the F-statistic could not be estimated, and this is reported as "not estimable" rather than as a P-value. Results are presented as treatment means with pooled SEM and associated P-values. Homogeneity of variance was not formally tested (e.g., by Levene's test) in the original analysis, which is acknowledged as a limitation. Given the large number of outcomes evaluated and the absence of adjustment for multiple comparisons, pairwise LSD comparisons should be regarded as exploratory, and individual P-values as nominal rather than multiplicity-adjusted. The ordered dose structure would also lend itself to linear and quadratic polynomial trend contrasts, which were not performed here and are recommended for future analyses.

3. Results

3.1 Physical quality of breast and thigh meat

Water-holding capacity, drip loss and cooking loss of breast meat did not differ significantly among treatments ($P = 0.626$, 0.724 and 0.147, respectively; Table 2). In thigh meat, water-holding capacity tended to be higher in birds fed 3 g/kg sumac (73.33%) than in the 1 g/kg group (61.11%), but the overall treatment effect was not significant ($P = 0.249$); a borderline effect was noted for thigh drip loss ($P = 0.072$). Notably, cooking loss of thigh meat decreased progressively with increasing sumac supplementation from 26.42% in the control to 5.74% in the 4 g/kg group ($P = 0.001$); values in the 3 g/kg (11.81%) and 4 g/kg (5.74%) groups were significantly lower than the control.

3.2 Chemical quality of breast and thigh meat

Muscle pH values fell within the range typical of chilled broiler meat and were not affected by dietary treatment (breast, $P = 0.125$; thigh, $P = 0.153$; Table 3). Lipid oxidation of thigh meat, expressed as TBARS, did not differ significantly among treatments ($P = 0.306$). In breast meat, however, TBARS values showed a numerical difference that was not

Table 2. Physical quality of breast and thigh meat of Cobb-500 broiler chicken in response to different levels (g/kg feed) of sumac

Variable	T1 (0 g/kg)	T2 (1 g/kg)	T3 (2 g/kg)	T4 (3 g/kg)	T5 (4 g/kg)	SEM	P-value
Breast meat							
Water-holding capacity (%)	63.33	62.22	61.11	63.33	66.67	1.133	0.626
Drip loss (%)	4.78	4.77	7.22	3.74	3.64	0.894	0.724
Cooking loss (%)	21.72	14.27	20.48	11.24	12.54	1.445	0.147
Thigh meat							
Water-holding capacity (%)	65.56	61.11	66.67	73.33	68.89	1.587	0.249
Drip loss (%)	0.69	1.94	2.59	1.69	0.98	0.196	0.072
Cooking loss (%)	26.42^{a}	14.96^{b}	15.56^{b}	11.81^{bc}	5.74^{c}	0.944	0.001

Means within a row bearing different superscripts differ significantly ($P < 0.05$); superscripts are shown only where the omnibus treatment effect was significant. SEM: Pooled standard error of the mean. n = 3 birds/treatment; the individual bird was the experimental unit

statistically nonsignificant ($P = 0.058$) and were numerically lowest in the 1 g/kg group (0.31 mg MDA/kg) compared with the control (0.41 mg MDA/kg) and the highest inclusion levels (0.42–0.43 mg MDA/kg), which may indicate a modest improvement in oxidative stability at the lowest inclusion rate, though this numerical pattern should not be over-interpreted; because the omnibus effect did not reach $P < 0.05$, no pairwise mean separation is presented for this variable.

3.3 Sensory characteristics of breast and thigh meat

No significant differences were detected among treatments for any breast-meat sensory attribute ($P > 0.05$; Table 4). For thigh meat, treatment differences were also non-significant for individual attributes except that overall acceptability revealed a borderline statistical result ($P = 0.050$; Table 5); the control and 3 g/kg groups received the highest scores (4.3), while the 2 g/kg group received the lowest score (3.9). Odor scores for thigh meat were identical (4.5) in every treatment group, so the between-group variance was zero and an F-statistic could not be estimated for this attribute.

3.4 Serum calcium and phosphorus

Serum calcium was not significantly affected by dietary sumac ($P = 0.325$), ranging from 7.07 mg/dL in the 4 g/kg group to 8.17 mg/dL in the 1 g/kg group (Table 6). In contrast, serum phosphorus was significantly influenced by treatment ($P = 0.021$); the highest concentration was observed in the 2 g/kg group (6.20 mg/dL), which was significantly greater than that of the control (5.17 mg/dL), 1 g/kg (5.53 mg/dL) and 4 g/kg (5.10 mg/dL) groups, with the 3 g/kg group (5.60 mg/dL) intermediate.

3.5 Duodenal histomorphology

Dietary sumac significantly influenced villus length ($P < 0.001$), villus width ($P < 0.001$), crypt depth ($P = 0.001$), villus: crypt ratio ($P < 0.001$) and estimated villus surface-area index ($P < 0.001$; Table 7). Villus length was markedly greater in the 1 g/kg (396.01 μm) and 2 g/kg (421.35 μm) groups than in the control (340.68 μm), 3 g/kg (350.68 μm) and 4 g/kg (328.01 μm) groups. A similar pattern was observed for villus width, with the highest values in the 1 g/kg (130.11 μm) and 2 g/kg (126.64 μm) groups. Crypt depth was significantly shallower in birds receiving 1 g/kg (101.03 μm) or 2 g/kg (97.70 μm) sumac than in the control (119.11 μm). Consequently, the villus:crypt ratio was highest at 2 g/kg (4.38) and 1 g/kg (4.08) compared with the control (2.89). The estimated villus surface-area index followed the same trend, being highest at 1 g/kg (161595 μm^2) and 2 g/kg (167576 μm^2) and lowest at 4 g/kg (103317 μm^2). Tunica muscularis thickness of the duodenum was not affected ($P = 0.726$) (Fig. 1).

3.6 Jejunal histomorphology

All measured indices except muscle-layer thickness were significantly influenced by dietary treatment ($P < 0.001$; Table 8). Villus length was greatest in the 1 g/kg (1442.68 μm) and 2 g/kg (1471.35 μm) groups, more than 30% higher than that in the control group (1107.35 μm). Villus width almost doubled in birds fed 1 g/kg (230.44 μm) or 2 g/kg (228.44 μm) sumac compared with the control (144.77 μm). Conversely, crypt depth decreased significantly at 1 g/kg (160.63 μm) and 2 g/kg

Table 3. Chemical quality (pH and lipid oxidation) of breast and thigh meat in response to different levels (g/kg feed) of sumac

Variable	T1 (0 g/kg)	T2 (1 g/kg)	T3 (2 g/kg)	T4 (3 g/kg)	T5 (4 g/kg)	SEM	P-value
Breast meat							
pH	6.23	5.97	6.33	6.27	6.53	0.060	0.125
TBARS (mg MDA/kg)	0.41	0.31	0.41	0.43	0.42	0.015	0.058
Thigh meat							
pH	6.73	6.53	6.63	6.70	6.90	0.042	0.153
TBARS (mg MDA/kg)	0.40	0.41	0.44	0.40	0.37	0.010	0.306

No omnibus treatment effect was significant at $P < 0.05$ in this table; accordingly, no pairwise superscripts are shown; TBARS, thiobarbituric acid-reactive substances; MDA, malondialdehyde. n = 3 birds/treatment; the individual bird was the experimental unit SEM: Pooled standard error of the mean; n = 3 birds/treatment; the individual bird was the experimental unit

Table 4. Sensory attributes of breast meat of Cobb-500 broiler chicken in response to different levels (g/kg feed) of sumac

Variable	T1 (0 g/kg)	T2 (1 g/kg)	T3 (2 g/kg)	T4 (3 g/kg)	T5 (4 g/kg)	SEM	P-value
Odor	4.5	4.5	4.5	4.7	4.5	0.033	0.452
Color	4.5	4.8	4.8	5.0	5.0	0.069	0.212
Texture	4.3	4.17	4.0	4.0	4.0	0.047	0.171
Taste	4.3	4.2	4.0	4.3	4.0	0.082	0.534
Appearance	4.5	4.2	4.3	4.2	4.4	0.073	0.529
Overall acceptability	4.4	4.4	4.3	4.4	4.4	0.028	0.808

Scores recorded on a 5-point hedonic scale (1 = dislike extremely, 5 = like extremely); No treatment effect was significant at $P < 0.05$; Three panelists evaluated cooked samples from the three birds/treatment used for meat-quality analysis; the sample was the experimental unit

Table 5. Sensory attributes of thigh meat of Cobb-500 broiler chicken in response to different levels (g/kg feed) of sumac

Variable	T1 (0 g/kg)	T2 (1 g/kg)	T3 (2 g/kg)	T4 (3 g/kg)	T5 (4 g/kg)	SEM	P-value
Odor	4.5	4.5	4.5	4.5	4.5	0.000	Not estimable*
Color	4.3	3.5	3.3	4.2	4.3	0.126	0.091
Texture	4.3	4.2	3.8	4.3	4.0	0.067	0.152
Taste	4.3	4.2	4.0	4.3	4.0	0.058	0.233
Appearance	4.2	3.9	3.7	4.2	4.2	0.079	0.229
Overall acceptability	4.3	4.0	3.9	4.3	4.2	0.061	0.050

*Scores recorded on a 5-point hedonic scale (1 = dislike extremely, 5 = like extremely). a-b Means within a row bearing different superscripts differ significantly ($P < 0.05$). Overall acceptability ($P = 0.050$) sits exactly at the significance threshold defined in Methods ($P < 0.05$) and, strictly, does not meet it; the pairwise letters above are shown for reference but should be interpreted with caution as a borderline, nominal result. *Odor scores were identical across all treatments (zero variance), so the F-statistic could not be estimated. Three panelists evaluated cooked samples from the three birds/treatment used for meat-quality analysis; the sample was the experimental unit for sensory scores*

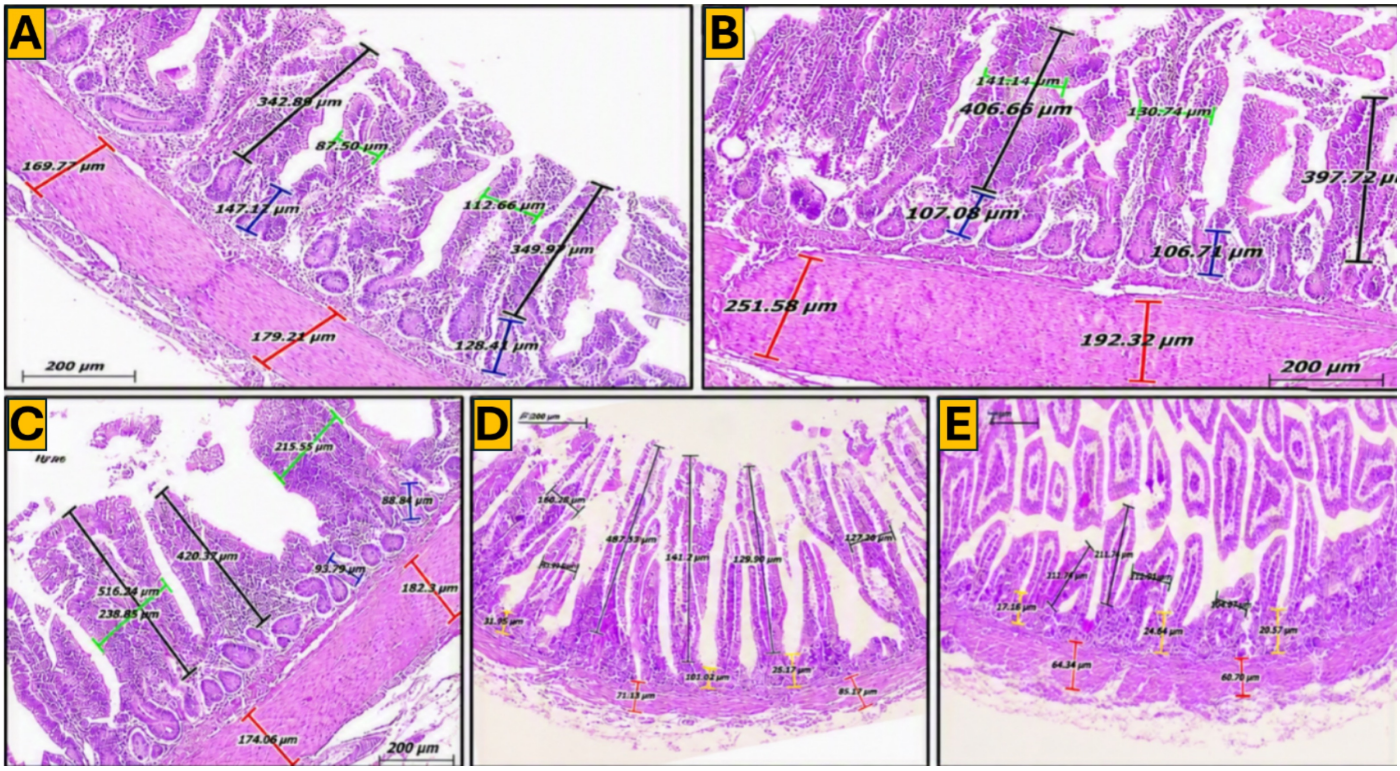

Fig. 1. Photomicrograph of the duodenum of broilers (35 days old). Histomorphology of these segments in the experimental groups was measured. Indices include: VL (black line), VW (green line), CD (blue line), and thickness of the tunica muscularis (red line). (H &E stain, scale bars 200 µm)

Table 6. Serum calcium and phosphorus concentrations of Cobb-500 broiler chicken in response to different levels (g/kg feed) of sumac

Variable	T1 (0 g/kg)	T2 (1 g/kg)	T3 (2 g/kg)	T4 (3 g/kg)	T5 (4 g/kg)	SEM	P-value
Calcium (mg/dL)	7.87	8.17	7.50	7.27	7.07	0.173	0.325
Phosphorus (mg/dL)	5.17^{b}	5.53^{b}	6.20^{a}	5.60^{ab}	5.10^{b}	0.090	0.021

Means within a row bearing different superscripts differ significantly ($P < 0.05$); n = 3 birds/treatment; the individual bird was the experimental unit

(150.63 μm) relative to the control (224.63 μm). Accordingly, the jejunal villus: crypt ratio rose from 5.02 in the control to 10.48 and 10.93 in the 1 and 2 g/kg groups, respectively, and the estimated villus surface-area index more than doubled in these two treatments. Higher inclusion levels (3 and 4 g/kg) did not sustain these improvements. Muscle-layer thickness was similar across all treatments ($P = 0.967$) (Fig. 2).

4. Discussion

The present experiment provides an integrated evaluation of the effects of graded dietary levels of *Rhus coriaria* powder on meat quality, serum mineral profile, and intestinal architecture in Cobb-500 broilers. The pattern of response was outcome-specific rather than uniform across endpoints: intestinal histomorphology and (nonsignificant) breast lipid oxidation were most favorably altered at low-to-moderate inclusion (1–2 g/kg), with apparent blunting at 3–4 g/kg, whereas thigh-meat cooking loss instead decreased progressively across the full dose range tested, with the greatest reduction at 4 g/kg, and serum phosphorus peaked specifically at 2 g/kg. This divergence indicates that no single inclusion level was optimal for every outcome measured. This inverted-U pattern is a well-recognized feature of polyphenol- and tannin-rich phytogenic additives, where beneficial antioxidant and antimicrobial actions at low doses can be counterbalanced at higher doses by tannin-mediated interference with protein digestion and mineral chelation (Batiha et al. 2022; Huang et al. 2018).

The most striking meat-quality finding was the marked reduction in thigh-meat cooking loss with increasing sumac inclusion, from 26.4% in the control to 5.7% at 4 g/kg. Cooking loss is a critical economic and technological trait because it directly determines the yield of ready-to-eat products and influences juiciness and consumer acceptability. Improved cooking yield is generally associated with enhanced integrity of muscle proteins and reduced oxidative damage to membrane lipids during heating (Honikel and Kim 1986; Lin et al. 2022). The polyphenols and hydrolysable tannins of sumac are potent free-radical scavengers (Abu-Reidah et al. 2015; Alsamri et al. 2021) and can stabilize sarcoplasmic and myofibrillar proteins against oxidative denaturation, thereby preserving water-binding capacity during cooking. Similar improvements in water retention and cooking properties have been reported when broilers were supplemented with other polyphenol-rich plants such as thyme, oregano, olive leaves and grape pomace (Abd El-Hack et al. 2022; Yang et al. 2015). Because cooking loss was assessed on a small number of samples per treatment (three birds/treatment, one cooking replicate per sample), and endpoint temperature rather than core temperature was used to define doneness, the magnitude of this effect should be interpreted with some

Table 7. Duodenal histomorphometric measurements of Cobb-500 broiler chicken in response to different levels (g/kg feed) of sumac

Variable	T1 (0 g/kg)	T2 (1 g/kg)	T3 (2 g/kg)	T4 (3 g/kg)	T5 (4 g/kg)	SEM	P-value
Villus length, VL (μm)	340.68^{b}	396.01^{a}	421.35^{a}	350.68^{b}	328.01^{b}	6.20	<0.001
Villus width, VW (μm)	102.78^{b}	130.11^{a}	126.64^{a}	106.64^{b}	100.64^{b}	1.47	<0.001
Crypt depth, CD (μm)	119.11^{a}	101.03^{bc}	97.70^{c}	116.03^{a}	111.77^{ab}	1.79	0.001
VL:CD ratio	2.89^{b}	4.08^{a}	4.38^{a}	3.03^{b}	2.94^{b}	0.076	<0.001
Estimated villus surface-area index (μm²)	109859^{b}	161595^{a}	167576^{a}	117846^{b}	103317^{b}	2707.6	<0.001
Tunica muscularis thickness (μm)	216.66	220.53	216.00	221.93	218.93	1.57	0.726

Means within a row bearing different superscripts differ significantly ($P < 0.05$); Estimated villus surface-area index = π × VW × VL (simplified cylindrical-geometry approximation); n = 5 birds/treatment (three cross-sections/bird, averaged); the individual bird was the experimental unit

Table 8. Jejunal histomorphometric measurements of Cobb-500 broiler chicken in response to different levels (g/kg feed) of sumac

Variable	T1 (0 g/kg)	T2 (1 g/kg)	T3 (2 g/kg)	T4 (3 g/kg)	T5 (4 g/kg)	SEM	P-value
Villus length, VL (μm)	1107.35^{b}	1442.68^{a}	1471.35^{a}	1144.01^{b}	1095.15^{b}	14.33	<0.001
Villus width, VW (μm)	144.77^{b}	230.44^{a}	228.44^{a}	174.57^{b}	146.71^{b}	7.40	<0.001
Crypt depth, CD (μm)	224.63^{a}	160.63^{b}	150.63^{b}	213.29^{a}	210.43^{a}	4.87	<0.001
VL:CD ratio	5.02^{b}	10.48^{a}	10.93^{a}	5.42^{b}	5.24^{b}	0.306	<0.001
Estimated villus surface-area index (μm²)	508003^{b}	1041444^{a}	1053276^{a}	620846^{b}	510239^{b}	31807.4	<0.001
Tunica muscularis thickness (μm)	249.26	249.93	244.26	250.26	252.26	3.89	0.967

Means within a row bearing different superscripts differ significantly ($P < 0.05$); Estimated villus surface-area index = π × VW × VL (simplified cylindrical-geometry approximation); n = 5 birds/treatment (three cross-sections/bird, averaged); the individual bird was the experimental unit

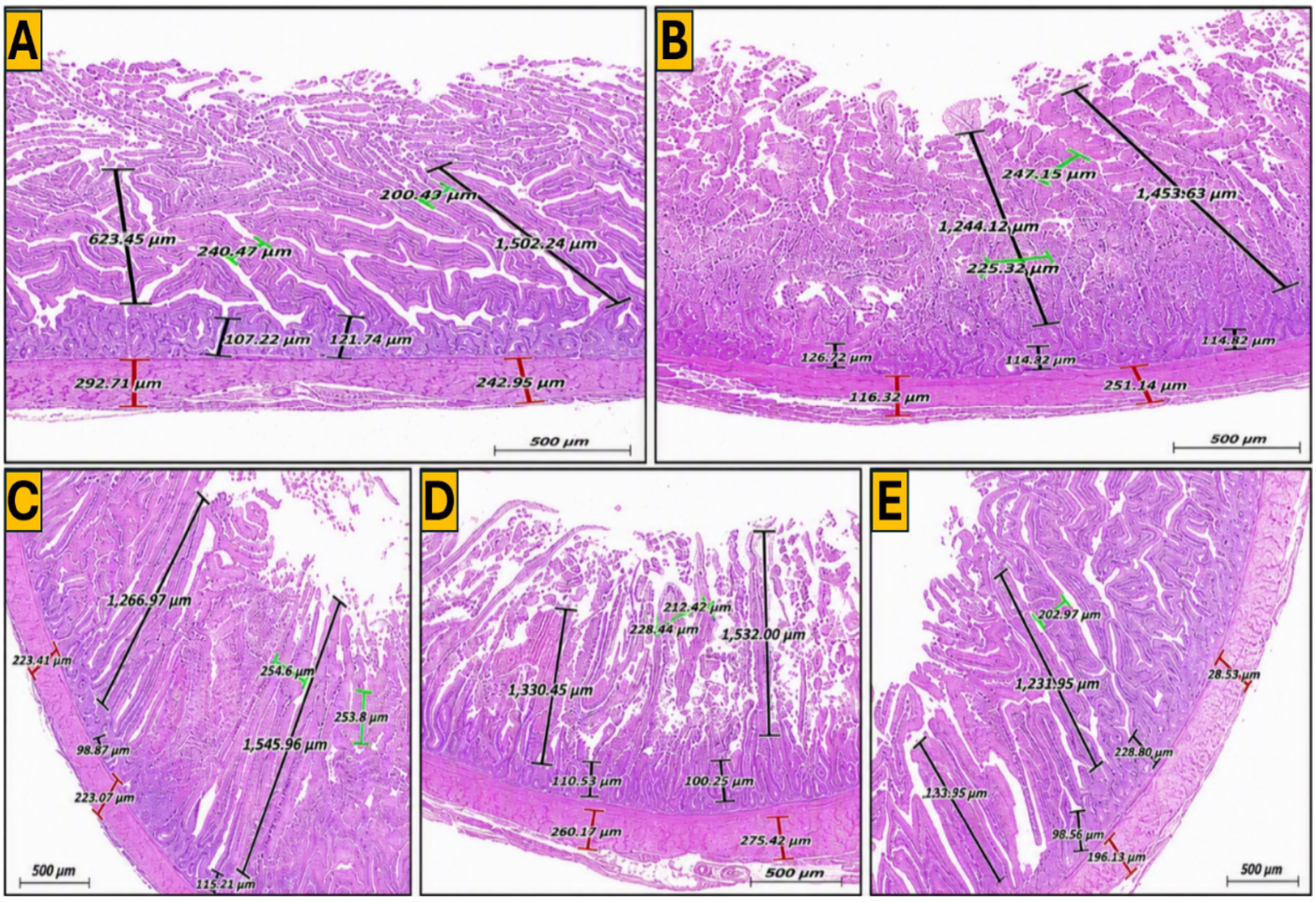

Fig. 2. *Photomicrograph of jejunum of broilers (35 days old). Histomorphology of these segments in the experimental groups was measured. Indices include: VL (black line), VW (green line), CD (blue line), and thickness of the tunica muscularis (red line). (H &E stain, scale bars 500 µm)*

caution pending replication with a larger sample size and a core-temperature cooking protocol; potential contributions from uncontrolled sample-to-sample variation in initial sample mass and dimensions, postmortem handling, and precise cooking duration cannot be excluded and should be standardized more rigorously in future studies.

In contrast, breast-meat physical parameters were not modified by sumac supplementation, most likely because breast (*Pectoralis major*) is composed almost exclusively of type IIB (fast-twitch, glycolytic) fibers with a low intramuscular fat content, making it inherently less susceptible to oxidative changes than the mixed-fiber, myoglobin- and lipid-rich thigh muscle (Lin et al. 2022). Consistent with this reasoning, the tendency toward lower TBARS values in breast muscle at 1 g/kg sumac (0.31 vs. 0.41 mg MDA/kg in the control) suggests that even the small oxidative pool of breast meat may have benefited from the antioxidant activity of sumac phenolics, although this result did not reach conventional statistical significance and should be treated as suggestive rather than conclusive. Comparable reductions in muscle malondialdehyde have been reported after dietary supplementation with sumac seed powder in broilers reared at high stocking density (Reda et al. 2026) and with other tannin-rich plants such as gallic acid, chestnut and quebracho (Huang et al. 2018). Interestingly, TBARS values in the highest inclusion groups (3-4 g/kg) tended to return toward control levels, an observation that mirrors the well-documented pro-oxidant behavior of polyphenols and tannins when consumed in excess, particularly in the presence of transition metal ions (Batiha et al. 2022).

Sensory attributes of breast meat were unaffected, indicating that consumer perception of odor, color, texture, taste and overall acceptability was not compromised, which is important because acceptability of any novel additive is a prerequisite for commercial adoption (Mellen et al. 2014). The decrease in overall acceptability of thigh meat in the 2 g/kg group (3.9 vs. 4.3 in the control) was small on the 5-point hedonic scale, sitting exactly at the conventional significance threshold and was based on the assessment by a three-member panel. A possible untested explanation can subtle changes in thigh color caused by the anthocyanin fraction of sumac, which is broadly consistent with observations by Ahmadian et al. (2020). However, this remains an unconfirmed hypothesis rather than a demonstrated mechanism and should be tested directly with a larger panel before being treated as a robust effect.

Sumac supplementation did not alter serum calcium, but the 2 g/kg diet significantly increased serum phosphorus compared with the control and the 1 and 4 g/kg groups (6.20 vs. 5.17, 5.53 and 5.10 mg/dL, respectively). Sumac fruits are themselves rich in phosphorus (Matthaus and Özcan 2014; Zannou et al. 2024), and the improvement in duodenal and jejunal absorptive architecture observed at the same inclusion level (see below) may have contributed to greater phosphorus

absorption, although mineral balance, bone ash and phosphate-transporter expression were not measured, so this mechanistic link remains inferential. Improved gut integrity, up-regulation of phosphate transporters and stimulation of intestinal alkaline phosphatase activity by phenolic compounds have been proposed as complementary mechanisms in previous studies (Kheiri et al. 2015; Reda et al. 2026). The return of serum phosphorus toward control values at 3 and 4 g/kg is consistent with a tannin–mineral complexation effect at higher inclusion rates, in which unabsorbed tannins bind divalent and multivalent cations in the intestinal lumen and reduce their bioavailability (Huang et al. 2018). The absence of an effect on serum calcium may indicate that calcium homeostasis in broilers is more tightly regulated by parathyroid hormone and 1,25-dihydroxycholecalciferol than phosphorus and is therefore less sensitive to short-term changes in intestinal absorption efficiency. A similar dissociation between plasma calcium and phosphorus responses to phytogenic additives has been documented in other broiler studies (Reda et al. 2026).

The most consistent finding of the present study was the marked improvement of intestinal histomorphology in birds fed 1-2 g/kg sumac. In both the duodenum and the jejunum, villus length, villus width and the estimated villus surface-area index were significantly greater, while crypt depth was significantly smaller, in these two groups than in the control or the higher-inclusion groups, resulting in villus: crypt ratios approximately 1.4-1.5-fold higher in the duodenum and more than 2-fold higher in the jejunum. Because the estimated villus surface-area index reflects the absorptive capacity of the small intestine, and shallower crypts indicate a lower rate of epithelial cell renewal and thus a lower maintenance cost of the mucosa, these results indicate altered, more favorable intestinal architecture at 1-2 g/kg sumac, a structural change generally associated with improved nutrient-absorptive potential, although digestibility, nutrient-transporter expression and absorptive function were not directly measured in this study (Kheiri et al. 2015; Mahmoud et al. 2025). The consistency of this pattern across two independent intestinal segments strengthens confidence in the biological signal, although mucosal oxidative status, digestive enzyme activity, epithelial permeability and microbiota composition were not measured in this study, so the mechanisms below remain plausible rather than directly demonstrated.

Several complementary mechanisms may explain this response. First, the phenolic compounds and hydrolysable tannins of sumac exert selective antimicrobial activity against enteric pathogens such as *E. coli*, *Salmonella* spp. and *Clostridium perfringens* while sparing or even promoting beneficial *Lactobacillus* and *Bifidobacterium* populations (Ahmadian et al. 2020; Alsamri et al. 2021; Reda et al. 2026). This favorable modulation of microbiota could reduce the release of pro-inflammatory bacterial metabolites and lipopolysaccharides, decreasing local inflammation, cryptal hyperplasia and villus atrophy. Second, sumac polyphenols may enhance the local antioxidant defense of enterocytes by up-regulating superoxide dismutase, catalase and glutathione peroxidase activities, as reported elsewhere (Reda et al. 2026), protecting the villus epithelium against oxidative injury. Third, sumac has been shown to stimulate the secretion and activity of intestinal digestive enzymes (amylase, lipase and protease) in other trials, improving nutrient hydrolysis and absorption (Reda et al. 2026). Finally, organic acids present in sumac (malic, citric and gallic) may lower intestinal pH, which could further inhibit acid-intolerant enteropathogenesis and support enterocyte energy metabolism.

A simple tannin-dose threshold may therefore not fully account for the plateau or reversal of benefits observed at 3–4 g/kg sumac. Other mechanisms, such as saturation of antioxidant or antimicrobial benefit, altered palatability, or interactions among different phytochemical fractions of sumac, may also contribute. These possibilities should be regarded as hypotheses requiring direct tannin assay and dose-ranging studies. At the highest inclusion level tested (4 g/kg feed), this corresponds to an estimated dietary tannin contribution of only ~0.6–1.0 g/kg feed (~0.06–0.10% of the diet) — well below the ≈2–3% dietary tannin concentration typically associated with anti-nutritional effects such as digestive-enzyme binding, reduced protein digestibility and mucosal irritation (Huang et al. 2018). Because sumac contains roughly 15–25% hydrolysable tannins on a dry-matter basis (Abu-Reidah et al. 2015), inclusion at 4 g/kg feed may deliver a tannin load approaching the threshold at which adverse effects become detectable in poultry, although the specific batch used here was not independently assayed for tannin content. Tunica muscularis thickness was unaffected in either intestinal segment, indicating that sumac primarily influenced the mucosal rather than the muscular layer of the intestinal wall.

The present findings are in broad agreement with previous studies on sumac in poultry, while adding new information on Cobb-500 broilers under standard commercial conditions. Reda et al. (2026) identified 3 g/kg sumac seed powder as the optimum inclusion level for high-stocking-density Arbor Acre broilers, whereas in the present study the optimum for meat quality and intestinal architecture was 1-2 g/kg. This apparent discrepancy may be reconciled by the different physiological states of the birds: chronic stocking-density stress imposes higher demands on antioxidant and immune defenses and may accommodate or even require a higher dose of a polyphenolic feed additive (Reda et al. 2026). Under standard, non-stressed conditions, as employed here, a lower dose may already provide maximum benefit, with higher doses triggering tannin-mediated anti-nutritional effects. Ahmadian et al. (2020) used markedly higher inclusion rates (1-3% of the diet, i.e. 10-30 g/kg) of whole sumac berries and reported reduced feed intake, reduced defeathered body weight at the two highest doses and a marked reduction in abdominal fat. The much lower doses used here (1-4 g/kg) did not compromise carcass quality or sensory attributes but did preserve the beneficial effects on lipid oxidation and gut architecture, suggesting that finely ground fruit powder may be more bioavailable, and therefore effective at lower doses, than whole-berry inclusion.

Overall, the results indicate that *Rhus coriaria* powder can be incorporated in commercial broiler diets at 1-2 g/kg feed with the potential to improve thigh-meat cooking yield, breast-meat oxidative stability, serum phosphorus status and, most notably, the absorptive architecture of the small intestine, without adversely affecting sensory quality. The candidate inclusion level (1–2 g/kg, i.e. 0.1–0.2% of the diet) is well below that of most other phytogenic feed additives and would, if confirmed, be economically attractive.

The present study has several limitations that should be considered when interpreting these findings and should be addressed in confirmatory work. First, meat-quality and serum outcomes were assessed in a small number of birds per treatment (three birds/treatment for meat and for serum), and no a priori sample-size or power calculation was reported; the precision and generalizability of these estimates should therefore be confirmed in an adequately

powered trial. Second, although dietary treatment was applied at the pen level, the individual bird was used as the experimental unit for carcass, meat-quality, serum and histomorphological traits, following common practice in broiler nutrition research; formal accounting for pen-level clustering with mixed models would further strengthen inference for these outcomes. Third, the sumac product used was a commercial food-grade powder that was not independently assayed for total phenolic or tannin content in this trial, so the tannin-mediated mechanisms proposed above remain inferential. Fourth, only two intestinal segments (duodenum and jejunum) were analyzed; future studies should include the ileum. Fifth, blood mineral analysis was restricted to calcium and phosphorus; a broader profile (Mg, Zn, Fe, Cu, Mn) would help clarify whether tannin–mineral interactions occur at higher inclusion levels. Sixth, growth performance and carcass yield data are the subject of a companion paper. Finally, potential effects on the cecal microbiota and on the expression of tight-junction and phosphate-transporter genes deserve further investigation.

5. Conclusions

Dietary supplementation of Cobb-500 broilers with *Rhus coriaria* (sumac) powder at 1-2 g/kg feed for 35 days significantly improved thigh-meat cooking yield, tended to enhance breast-meat oxidative stability, increased serum phosphorus concentration and markedly improved duodenal and jejunal villus length, villus width and villus: crypt ratio while decreasing crypt depth. Higher inclusion levels (3-4 g/kg) offered no additional benefit for intestinal histomorphology and, for several indices, blunted the response — a pattern that may be consistent with anti-nutritional effects of dietary tannins, although the calculated tannin contribution at these doses was well below the threshold conventionally associated with such effects. By contrast, thigh-meat cooking loss improved progressively up to 4 g/kg and serum phosphorus was highest at 2 g/kg, underscoring that the optimal inclusion level is outcome-specific rather than uniform. *Rhus coriaria* powder is therefore a promising candidate natural feed additive at 1-2 g/kg feed to alter intestinal histomorphology, and at levels up to 4 g/kg where improved cooking yield is prioritized. The supplementation was well tolerated at all doses tested up to 4 g/kg over the 35-day trial, although this study was not designed as a formal safety or toxicological assessment, pending confirmation in adequately powered, independently replicated trials that also characterize the tannin content of the test material. Further work should explore its interactions with growth performance, cecal microbiota and immune-related gene expression, as well as effects on the ileal segment and on a wider range of blood minerals.

Declarations

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Conflict of interest: The authors declare that they have no conflicts of interest

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Ethics approval: Ethical clearance was obtained from the Institutional Review Board and the Medical Ethics Committee of the Faculty of Veterinary Medicine, King Faisal University (Approval No. KFU-344/2026)

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