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Dietary Coffee Silverskin Supplementation: Effect on Growth Performance, Carcass Traits, and Gastrointestinal Health of Broilers

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Simple Summary

Coffee silverskin is a natural by-product of coffee roasting that contains bioactive and prebiotic compounds. This study investigated the effects of dietary coffee silverskin supplementation on growth performance, carcass traits, and gastrointestinal health in broiler chickens. The results suggest that coffee silverskin is a promising functional feed ingredient that can improve broiler growth performance and gut health.

Abstract

Coffee silverskin (CSS) remains a neglected poultry additive; investigating its bioactive potential is essential for optimizing agricultural productivity and enhancing food security via advanced nutrition. This study analyzed how dietary CSS supplementation influences broiler growth, slaughter characteristics, meat quality, cecal microbial ecology, and intestinal histomorphology. A total of 400 one-day-old male Ross 308 broilers were randomly assigned to four dietary treatments with 10 replicates of 10 birds each. Experimental treatments consisted of a negative control (NC, basal diet) and CSS-supplemented groups (0.5, 1.0, and 2.0 g/kg, designated CSS0.5, CSS1.0, and CSS2.0, respectively). All data were subjected to one-way ANOVA using the procedure of SPSS 23.0. Coffee silverskin supplementation, specifically at 1.0–2.0 g/kg, optimized broiler growth performance, significantly elevating body weight and average daily gain ($p < 0.05$). While carcass yield improved in a dose-dependent manner, fundamental meat quality—pH and shear force—remained stable. Crucially, CSS inclusion reconfigured cecal ecology, selectively suppressing *Escherichia coli* and *Salmonella* sp. while enhancing *Lactobacillus* populations ($p < 0.001$). This microbial shift mirrored histological gains, notably enhanced villus height and villus height-to-crypt ratios ($p < 0.05$). These findings demonstrate that CSS, particularly at 1.0–2.0 g/kg, enhances broiler performance, carcass quality and gut health.

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Keywords: coffee silverskin; broiler performance; gut microbiota; meat quality; intestinal morphology

1. Introduction

The environmental burden of industrial waste has emerged as a critical global challenge, with particular attention being paid to sustainable waste management solutions across various sectors [1]. Within the food production industry, coffee processing generates substantial by-products, with global coffee silverskin (CSS) production estimated at approximately 1.8 million metric tons annually [2]. This thin epidermal layer, discarded during bean roasting, represents both an environmental liability and an untapped resource rich in bioactive compounds [3].

Recent investigations have revealed that CSS contains significant quantities of phenolic compounds, caffeine, and chlorogenic acids—bioactive molecules with demonstrated health benefits, including antidiabetic, anti-inflammatory, and antioxidant properties [4,5]. The substantial dietary fiber content [3,6] and prebiotic potential [7] of CSS have prompted research into its applications as a functional food additive [8]. Furthermore, CSS demonstrates promising lipid-modulating effects, including the ability to improve high-density lipoprotein cholesterol profiles [9] and regulate adipocyte metabolism [10].

The livestock industry faces mounting pressure to identify sustainable alternatives to antibiotic growth promoters, particularly in poultry production [11]. Current research indicates that dietary antioxidants and fiber sources can significantly improve intestinal health and disease resistance in poultry [12,13]. While preliminary studies in aquaculture systems have demonstrated CSS's efficacy in enhancing growth performance and immune parameters in tilapia [7,14], research examining its application in terrestrial livestock remains notably scarce.

This study systematically investigates the effects of dietary CSS supplementation on Ross 308 broiler chickens, specifically evaluating growth performance parameters, carcass characteristics and meat quality, cecal microbiota composition, and small intestinal morphology to address critical knowledge gaps in sustainable poultry nutrition.

Our findings contribute to the growing body of research on sustainable agricultural practices by evaluating the potential of CSS as both a functional feed additive and a means of valorizing coffee processing by-products. The results may inform strategies for improving poultry production efficiency while addressing environmental concerns associated with industrial food waste.

2. Materials and Methods

2.1. Preparation of Coffee Silverskin

Coffee silverskin used in this study was obtained from Saenchai Estate. Briefly, the CSS samples were dried at 60 °C for 48 h and subsequently ground using a grinder (Cutting Mill SM 100, Retsch, Haan, Germany) into a powder, which passed through a 1 mm sieve, producing the CSS powder. Proximate analysis of CSS (Table 1) was conducted according to AOAC [15]. The bioactive compounds in CSS, including total phenolic compounds, 2,2-diphenyl-1-picrylhydrazyl (DPPH), total flavonoid compounds, caffeine, epicatechin, and gallic acid, were determined according to Nhu-Trang et al. [16], and the results are presented in Table 2.

Table 1. Nutrient composition (air dry basis) of coffee silverskin.

Item	Coffee Silverskin
Dry matter	93.00
Organic matter	5.08
Crude protein	14.40
Crude fiber	39.02
Ether extract	0.03
Nitrogen free extract	34.48

Table 2. Bioactive compounds of coffee silverskin.

Item [1]	Coffee Silverskin
Total phenolic compounds, mg GE/g	2.00
DPPH, μmol TE/g	11.02
Total flavonoid compounds, mg QE/g	63.54
Caffeine, mg/100 g	1440.40
Epicatechin, mg/100 g	42.93
Gallic acid, mg/100 g	5.48

[1] GE: gallic acid; DPPH: 2,2-diphenyl-1-picrylhydrazyl; TE: trolox equivalent; QE: quercetin.

2.2. Animals and Experimental Design

A total of 400 one-day-old male Ross 308 broilers were randomly allocated to 4 groups of 10 replicates each, with 10 birds per replicate. The negative control (NC) group was fed a basal diet, and 3 CSS test groups were fed the basal diet plus 0.5, 1.0, and 2.0 g/kg (CSS0.5, CSS1.0, and CSS2.0, respectively) for 35 d. The chicks were fed starter diets from day 1 to day 14 and finisher diets from day 15 to day 35, based on the nutrient requirements for broilers according to NRC [17] (Table 3), and proximate analysis of the basal diets was conducted according to AOAC [15]. The chicks were raised in floor pens (100 cm × 100 cm × 80 cm), provided with supplemental heat and ventilation, and given free access to feed and water. The lighting program was provided continuously for the first week. The duration was gradually reduced (1 h per d) to 18 h by day 13, which was maintained throughout the study. The initial temperature was 32 °C, which was gradually lowered by 2 to 3 °C per week until reaching 25 °C.

Table 3. Composition of the basal diet for the starter and finisher phase.

Item	Starter (1–14 d)	Finisher (15–35 d)
Ingredients (% air dry basis)		
Yellow corn	57.17	59.58
Raw rice bran	5.00	5.00
Soybean meal (48% CP)	28.62	20.74
Rapeseed meal (38% CP)	3.20	6.00
Pork meal (50% CP)	3.00	4.00
Soybean oil	-	2.94
Salt	0.26	0.14
L-lysine	0.10	0.08
DL-methionine	0.25	0.15
Biofoss (21% P) [1]	0.70	0.02
Calcium carbonate	1.07	0.64
Premixes [2]	0.63	0.71
Total	100.00	100.00

Table 3. *Cont.*

Item	Starter (1–14 d)	Finisher (15–35 d)
Calculated composition		
Metabolizable energy (kcal/kg)	2987.89	3095.98
Calcium, %	0.61	0.41
Available phosphorus, %	0.59	0.39
Digestible lysine, %	1.20	1.12
Digestible Met, %	0.57	0.48
Digestible Met + Cys, %	0.92	0.80
Digestible tryptophan, %	0.26	0.25
Nutrient composition (% dry matter as fed)		
Dry matter	96.65	96.50
Organic matter	95.00	94.85
Crude protein	22.17	19.51
Crude fiber	2.22	3.15
Ether extract	6.31	6.57
Nitrogen free extract	60.96	62.12
Gross energy (cal/g)	4147.67	4324.00

[1] Biofoss supplies per kg of diet: monocalcium phosphate 1000 g, calcium 150 g, phosphorus 210 g, and fluorine 0.21%. [2] Mineral premix supplies per kg of diet: vitamin A 20,000,000 IU, vitamin D3 4,000,000 IU, vitamin E 11,000 IU, vitamin K3 4.00 g, vitamin B1 5.00 g, vitamin B2 10.00 g, vitamin B6 5.00 g, vitamin B12 0.02 g, vitamin C 15.00 g, pantothenic acid 15.00 g, folic acid 3.00 g, nicotinic acid 40.00 g, biotin 0.20 g, magnesium 100.00 g, potassium 90.00 g, sodium 100.00 g, and feed additive 25.30 g.

2.3. Growth Performance Measurements

The chicks were weighed weekly throughout the experimental period. The daily feed intake was recorded by measuring the amount of feed offered and the feed remaining during the starter, finisher and entire experimental periods. The average daily gain (ADG), average daily feed intake (ADFI) and feed conversion ratio (FCR) were calculated. Mortality was recorded daily throughout the experimental period.

$$\text{ADFI} = \text{feed intake}/(\text{day on feed} \times \text{number of broilers}) \quad (1)$$

$$\text{ADG} = (\text{finale weight} - \text{initial weight})/(\text{day on feed} \times \text{number of broilers}) \quad (2)$$

$$\text{FCR} = \text{Total feed intake}/\text{weight gain} \quad (3)$$

2.4. Slaughter Traits

At day 35, the birds were randomly weighed and slaughtered (10 broilers per treatment). After defeathering, the carcass (without feathers, blood, and internal organs) was weighed to determine carcass percentage, which was expressed as a percentage of live body weight. Breast and thigh muscles were weighed separately. Internal organs, including the liver, spleen, heart, proventriculus, gizzard, small intestine, cecum, and abdominal fat, were excised, weighed and calculated as a percentage of live weight. The meat parts (breast and thigh) were promptly placed in separate sealable plastic bags and kept at 4 °C for subsequent meat quality analysis [18]. At 24 h post-slaughter, the pH values were measured using a portable pH meter and the breast and thigh meats were measured for color parameters using a Minolta Chroma Meter (Model CR-410, Minolta Camera Co., Ltd., Osaka, Japan) [19]. According to Qu et al.'s method [20], shear force and cooking loss were evaluated. Meat samples, each weighing 50–60 g, were gently dried using tissue paper to remove surface moisture before their weights were recorded. Individual samples were placed in heat-resistant bags, sealed, and cooked in an 80 °C water bath for 20 min. The samples were removed and cooled at room temperature for 30–35 min and gently dried to remove excess liquid. Cooking loss was calculated as (raw meat weight − cooked meat

weight)/raw meat weight × 100. Shear force was evaluated by cutting the cooked meat into square pieces (1.27 cm thick) and measuring the cutting force with a mechanical device (Instron Model 3433 Universal Test Machine, Instron, Norwood, MA, USA).

2.5. Cecal Microbial

At the end of the trial (10 broilers per treatment), cecal digesta were collected and analyzed for bacterial content following a modified procedure by Qiu et al. [21]. Cecal digesta (1 g) was mixed with 9 mL of 0.1% peptone solution in sterile sampling tubes using a vortex mixer (LMS Co., Ltd., Bunkyo-ku, Tokyo, Japan). Serial dilutions were prepared, and the samples were plated onto specific agar media: Lactobacillus Man Rogosa Sharpe (MRS) Agar (Himedia Laboratories, Maharashtra, India) for isolating and culturing *Lactobacillus* sp., Xylose-Lysine Deoxycholate (XLD) Agar for *Salmonella* sp., and Eosin Methylene Blue (EMB) Agar for *Escherichia coli*. The XLD and EMB agar plates were incubated for 24 h, while the Lactobacillus MRS agar plates were incubated for 48 h at 37 °C. Bacterial colonies were counted immediately after incubation, and the results were presented as $\log_{10}$ colony-forming units per gram (cfu/g) of cecal content.

2.6. Small Intestine Histology Measurements

The small intestines (duodenum, jejunum, and ileum) were collected from the birds (10 birds per treatment) after slaughter in 1 cm sections and cleaned with phosphate-buffered saline before being preserved in a 10% formaldehyde solution for 24 h. The samples were then processed through a standardized protocol that included dehydration, clearing, and embedding in paraffin wax [22]. Using a rotary microtome, the tissues embedded in paraffin were sectioned into slices (4 μm thick) and positioned on glass slides. The sections were deparaffinized and stained with hematoxylin and eosin (H&E). Then, the tissue samples were mounted using a coverslip for observation. Histological examination was conducted with a compound microscope (A1 Zeiss Axio Scope, Carl Zeiss, Göttingen, Germany) at 10× magnification. Measurements of villus height (VH), crypt depth (CD), and villus height to crypt depth ratio (VH:CD) were taken using Motic Images Plus 2.0 software (Motic China Group Co., Xiamen, China) [23].

2.7. Statistical Analysis

The experimental data were analyzed by one-way ANOVA using SPSS 23.0 software (SPSS Inc., Chicago, IL, USA), followed by Duncan's multiple range test. The results are expressed as treatment means with the pooled standard error of the mean (SEM). Significant differences were accepted at $p < 0.05$. The effects of different levels of CSS supplementation were analyzed using linear and quadratic contrasts.

3. Results

3.1. Growth Performance

The effects of CSS on growth performance are presented in Table 4. By day 14, birds receiving CSS at 0.5 and 1.0 g/kg (CSS0.5 and CSS1.0, respectively) demonstrated significantly higher body weight and ADG compared to the negative control (NC; $p = 0.009$), a trend that persisted through day 35, with all CSS groups maintaining superior growth performance ($p = 0.005$). ADFI varied by treatment and phase ($p < 0.001$), with CSS0.5 consistently eliciting the highest ADFI. Feed conversion ratio outcomes showed phase-dependent differences, with CSS1.0 and CSS2.0 exhibiting efficiency, and CSS2.0 achieving the best overall FCR ($p = 0.006$). Linear and quadratic contrasts indicated dose-dependent responses for growth performance parameters, including body weight and ADG at 35 d ($p < 0.05$). Mortality did not differ significantly among the treatment groups.

Table 4. Effect of coffee silverskin-supplemented diets on the growth performance of broiler chickens [1].

Item	NC	CSS0.5	CSS1.0	CSS2.0	SEM	*p*-Value		
						T	L	Q
Body weight, g								
1 d	46.20	46.80	46.40	46.40	0.407	0.969	-	-
14 d	398.60 ^{b}	483.40 ^{a}	454.00 ^{a}	442.60 ^{ab}	9.832	0.009	0.412	0.017
35 d	1900.60 ^{b}	2115.00 ^{a}	2094.60 ^{a}	2109.00 ^{a}	27.904	0.005	0.026	0.022
Average daily gain, g/d								
1 to 14 d	25.17 ^{b}	31.18 ^{a}	29.11 ^{a}	28.30 ^{ab}	0.699	0.009	0.410	0.017
15 to 35 d	71.52 ^{b}	77.70 ^{a}	78.12 ^{a}	79.35 ^{a}	1.104	0.039	0.020	0.115
1 to 35 d	52.98 ^{b}	59.09 ^{a}	58.52 ^{a}	58.93 ^{a}	0.797	0.005	0.026	0.022
Average daily feed intake, g/d								
1 to 14 d	30.24 ^{d}	37.74 ^{a}	32.60 ^{c}	34.00 ^{b}	0.624	<0.001	0.368	0.050
15 to 35 d	106.14 ^{d}	127.46 ^{a}	116.68 ^{b}	112.50 ^{c}	1.780	<0.001	0.931	0.001
1 to 35 d	75.78 ^{d}	91.57 ^{a}	83.05 ^{b}	81.10 ^{c}	1.303	<0.001	0.809	0.002
Feed conversion ratio								
1 to 14 d	1.20	1.21	1.13	1.21	0.023	0.540	0.982	0.326
15 to 35 d	1.49 ^{b}	1.64 ^{a}	1.49 ^{b}	1.42 ^{b}	0.025	0.004	0.056	0.093
1 to 35 d	1.44 ^{b}	1.55 ^{a}	1.42 ^{b}	1.38 ^{b}	0.020	0.006	0.060	0.194
Mortality, %	2.00	0.00	1.00	0.00	0.422	0.283	0.197	0.570

[1] NC: basal diet; CSS0.5: basal diet with coffee silverskin at 0.5 g/kg; CSS1.0: basal diet with coffee silverskin at 1.0 g/kg; CSS2.0: basal diet with coffee silverskin at 2.0 g/kg. ^{a,b,c,d} Significant differences among treatment means within the same row are indicated by different letters ($p < 0.05$). SEM: standard error of the mean (n = 10). T indicates the *p*-value for the treatment effect; L and Q indicate the *p*-values for the linear and quadratic contrasts of CSS supplementation, respectively.

3.2. Slaughter Performance and Meat Quality

The effects of CSS on the slaughter performance of broiler chickens are shown in Table 5. CSS supplementation led to an increase in final live weight ($p = 0.004$), with CSS1.0 achieving the highest value and significantly exceeding NC, a pattern mirrored in defeather and carcass weights ($p = 0.003$ and $p = 0.008$, respectively), while CSS1.0 notably improved carcass percentage ($p = 0.046$). Likewise, there was a linear and quadratic improvement in live weight, defeather weight, and carcass weight in broilers that received CSS ($p < 0.05$). Additionally, CSS enhanced meat composition by increasing breast and thigh meat yields ($p = 0.012$ and $p = 0.043$), and although most visceral organ weights remained unchanged ($p > 0.05$), the CSS groups tended to exhibit lower gizzard weights and reduced abdominal fat.

A comprehensive evaluation of meat quality parameters—including physicochemical properties, instrumental color, and texture—revealed no significant differences across treatment groups ($p > 0.05$), indicating that CSS supplementation at varying inclusion levels did not affect post-mortem pH, color stability, cooking loss, or shear force, thereby preserving overall meat quality characteristics (Table 6). Supplementation with CSS showed no significant linear or quadratic effects on physicochemical properties, instrumental color, and texture ($p > 0.05$). However, a linear decrease was observed in breast meat color (b*) with increasing dietary CSS concentration.

Table 5. Effect of coffee silverskin-supplemented diets on the carcass quality of broiler chickens [1].

Item	NC	CSS0.5	CSS1.0	CSS2.0	SEM	*p*-Value		
						T	L	Q
Live weight, g	1898.00 [b]	2096.00 [a]	2102.00 [a]	2098.00 [a]	26.639	0.004	0.021	0.010
Defeather weight, g	1756.00 [b]	1988.00 [a]	1968.00 [a]	1974.00 [a]	28.931	0.003	0.026	0.012
Carcass weight, g	1541.14 [b]	1693.20 [a]	1782.30 [a]	1765.10 [a]	30.585	0.008	0.009	0.022
Carcass percentage, %	81.13 [b]	80.77 [b]	84.81 [a]	84.05 [ab]	0.653	0.046	0.041	0.379
Carcass composition, % lw								
Neck	4.54	4.07	4.19	4.21	0.130	0.650	0.562	0.365
Head	2.33	2.05	2.13	2.15	0.047	0.214	0.393	0.136
Wing	7.55	7.04	6.98	7.25	0.202	0.784	0.727	0.339
Drumstick	10.62	9.93	9.68	9.37	0.182	0.077	0.013	0.321
Shank	3.45	3.16	3.09	3.23	0.062	0.174	0.323	0.047
Skeleton	17.74	18.50	17.58	18.87	0.225	0.127	0.150	0.495
Meat percentage, % lw								
Breast	11.49 [b]	12.32 [ab]	13.19 [a]	12.90 [a]	0.214	0.012	0.014	0.027
Thigh	11.39 [b]	12.69 [a]	12.45 [a]	12.10 [ab]	0.179	0.043	0.420	0.019
Inner organ percentage, % lw								
Liver	1.89	1.87	1.75	1.88	0.044	0.656	0.861	0.319
Spleen	0.08	0.06	0.06	0.06	0.003	0.377	0.154	0.285
Heart	0.45	0.35	0.38	0.40	0.015	0.063	0.570	0.033
Proventriculus	0.38	0.34	0.34	0.33	0.011	0.339	0.144	0.346
Gizzard	2.66	2.20	2.32	2.12	0.078	0.058	0.037	0.293
Small intestine	3.22	3.52	3.47	3.06	0.083	0.161	0.307	0.046
Cecum	0.63	0.68	0.63	0.64	0.020	0.780	0.892	0.846
Abdominal fat	0.38	0.24	0.27	0.34	0.024	0.183	0.903	0.047

[1] NC: basal diet; CSS0.5: basal diet with coffee silverskin at 0.5 g/kg; CSS1.0: basal diet with coffee silverskin at 1.0 g/kg; CSS2.0: basal diet with coffee silverskin at 2.0 g/kg. [a,b] Significant differences among treatment means within the same row are indicated by different letters ($p < 0.05$). SEM: standard error of the mean (n = 10). T indicates the *p*-value for the treatment effect; L and Q indicate the *p*-values for the linear and quadratic contrasts of CSS supplementation, respectively.

Table 6. Effect of coffee silverskin-supplemented diets on the meat quality of broiler chickens [1].

Item	NC	CSS0.5	CSS1.0	CSS2.0	SEM	*p*-Value		
						T	L	Q
pH 24 h	5.80	5.53	5.49	5.50	0.050	0.079	0.059	0.082
Color of breast								
Lightness; L*	54.85	54.14	54.55	54.39	0.318	0.902	0.771	0.726
Redness; a*	1.30	1.44	1.44	1.48	0.051	0.645	0.273	0.541
Yellowness; b*	12.79	12.07	11.49	11.50	0.226	0.131	0.042	0.191
Shear force, kgf/cm^2	3.27	3.31	3.29	3.28	0.008	0.292	0.917	0.362
Cooking loss, %	25.42	25.43	25.33	25.43	0.030	0.658	0.983	0.411
Color of thigh								
Lightness; L*	54.08	53.53	53.27	54.12	0.301	0.728	0.872	0.258
Redness; a*	1.56	1.53	1.54	1.42	0.074	0.919	0.493	0.849
Yellowness; b*	11.18	11.06	10.81	11.05	0.260	0.972	0.852	0.686
Shear force, kgf/cm^2	4.07	4.11	4.09	4.08	0.008	0.240	0.897	0.284
Cooking loss, %	20.02	20.03	19.93	20.03	0.030	0.658	0.983	0.411

[1] NC: basal diet; CSS0.5: basal diet with coffee silverskin at 0.5 g/kg; CSS1.0: basal diet with coffee silverskin at 1.0 g/kg; CSS2.0: basal diet with coffee silverskin at 2.0 g/kg. SEM: standard error of the mean (n = 10). T indicates the *p*-value for the treatment effect; L and Q indicate the *p*-values for the linear and quadratic contrasts of CSS supplementation, respectively.

3.3. Cecal Microbiota

The effects of CSS on cecal bacterial microbiota are shown in Table 7. The CSS2.0 exhibited the most pronounced reduction in pathogenic bacteria, with *E. coli* counts significantly lower compared to the NC. Coffee silverskin supplementation showed a dose-dependent inhibitory effect on *E. coli*, with CSS2.0 demonstrating superior efficacy among CSS treatments ($p < 0.001$). A similar pattern was observed for *Salmonella* sp., where CSS achieved significant suppression compared to NC ($p < 0.001$). Coffee silverskin supplementation significantly enhanced *Lactobacillus* sp. populations in a dose-dependent manner ($p < 0.001$). The highest CSS doses (CSS1.0 and CSS2.0) promoted the most substantial increases, exceeding those of the NC. This stimulatory effect was particularly notable at inclusion levels ≥1.0 g/kg. Notably, CSS supplementation resulted in a significant quadratic response in cecal contents with increasing dietary CSS levels ($p < 0.05$).

Table 7. Effect of coffee silverskin-supplemented diets on the cecal microbiota (log_{10} CFU/g) of broiler chickens [1].

Item	NC	CSS0.5	CSS1.0	CSS2.0	SEM	*p*-Value		
						T	L	Q
Escherichia coli	7.32 [a]	7.17 [b]	7.11 [c]	7.03 [d]	0.031	<0.001	<0.001	0.001
Salmonella sp.	7.04 [a]	6.25 [b]	6.21 [b]	6.20 [b]	0.108	<0.001	<0.001	<0.001
Lactobacillus sp.	7.31 [c]	7.38 [b]	8.15 [a]	8.21 [a]	0.127	<0.001	0.757	<0.001

[1] NC: basal diet; CSS0.5: basal diet with coffee silverskin at 0.5 g/kg; CSS1.0: basal diet with coffee silverskin at 1.0 g/kg; CSS2.0: basal diet with coffee silverskin at 2.0 g/kg. [a,b,c,d] Significant differences among treatment means within the same row are indicated by different letters ($p < 0.05$). SEM: standard error of the mean (n = 10). T indicates the *p*-value for the treatment effect; L and Q indicate the *p*-values for the linear and quadratic contrasts of CSS supplementation, respectively.

3.4. Small Intestine Histology

As shown in Table 8 and Figure 1, CSS supplementation induced significant, dose-dependent improvements in intestinal morphology across all segments of the small intestine, with the most pronounced effects observed at the 2.0 g/kg inclusion level (CSS2.0). In the duodenum, CSS2.0 treatment resulted in maximal VH (1210.15 vs. 1025.35 μm; $p = 0.016$) and optimal VH:CD ($p = 0.021$), representing an 18.0% increase in absorptive surface area, while CD remained unaffected ($p = 0.112$). Similar responses were observed in the jejunum, where CSS2.0 elicited the highest VH (1059.70 vs. 915.62 μm; $p = 0.007$) and the most favorable VH:CD ($p = 0.013$). The ileum showed significant morphological adaptations to both CSS1.0 and CSS2.0, with VH increases of 9.8% and 8.7%, respectively, compared to NC (659.39 μm; $p = 0.004$), accompanied by enhanced VH:CD (4.30 and 4.43; $p = 0.004$). Notably, crypt depth remained stable across all intestinal segments and treatment groups ($p > 0.05$). Linear and quadratic contrast analyses demonstrated significant dose-dependent effects of dietary CSS supplementation on VH and VH:CD across the small intestine ($p < 0.05$).

Table 8. Effect of coffee silverskin-supplemented diets on the small intestine histology of broiler chickens [1].

Item	NC	CSS0.5	CSS1.0	CSS2.0	SEM	*p*-Value		
						T	L	Q
Duodenum								
VH, μm	1025.35 [b]	1080.80 [b]	1045.30 [b]	1210.15 [a]	23.204	0.016	0.003	0.236
CD, μm	193.08	196.74	179.08	201.51	3.492	0.122	0.030	0.308
VH:CD	5.33 [b]	5.49 [b]	5.83 [ab]	6.06 [a]	0.095	0.021	0.160	0.009
Jejunum								
VH, μm	915.62 [b]	901.20 [b]	925.88 [b]	1059.70 [a]	19.163	0.007	0.002	0.101
CD, μm	228.66	232.32	209.97	225.16	3.529	0.118	0.471	0.187
VH:CD	4.11 [b]	3.93 [b]	4.44 [ab]	4.71 [a]	0.095	0.013	0.004	0.610
Ileum								
VH, μm	659.39 [b]	667.28 [b]	723.93 [a]	716.81 [a]	8.350	0.004	0.746	0.001
CD, μm	172.77	170.52	169.38	162.12	2.014	0.276	0.670	0.083
VH:CD	3.85 [b]	3.95 [b]	4.35 [a]	4.46 [a]	0.074	0.004	0.995	<0.001

[1] NC: basal diet; CSS0.5: basal diet with coffee silverskin at 0.5 g/kg; CSS1.0: basal diet with coffee silverskin at 1.0 g/kg; CSS2.0: basal diet with coffee silverskin at 2.0 g/kg. VH: villus height; CD: crypt depth; VH:CD: villus height to crypt depth ratio. [a,b] Significant differences among treatment means within the same row are indicated by different letters ($p < 0.05$). SEM: standard error of the mean (n = 10). T indicates the *p*-value for the treatment effect; L and Q indicate the *p*-values for the linear and quadratic contrasts of CSS supplementation, respectively.

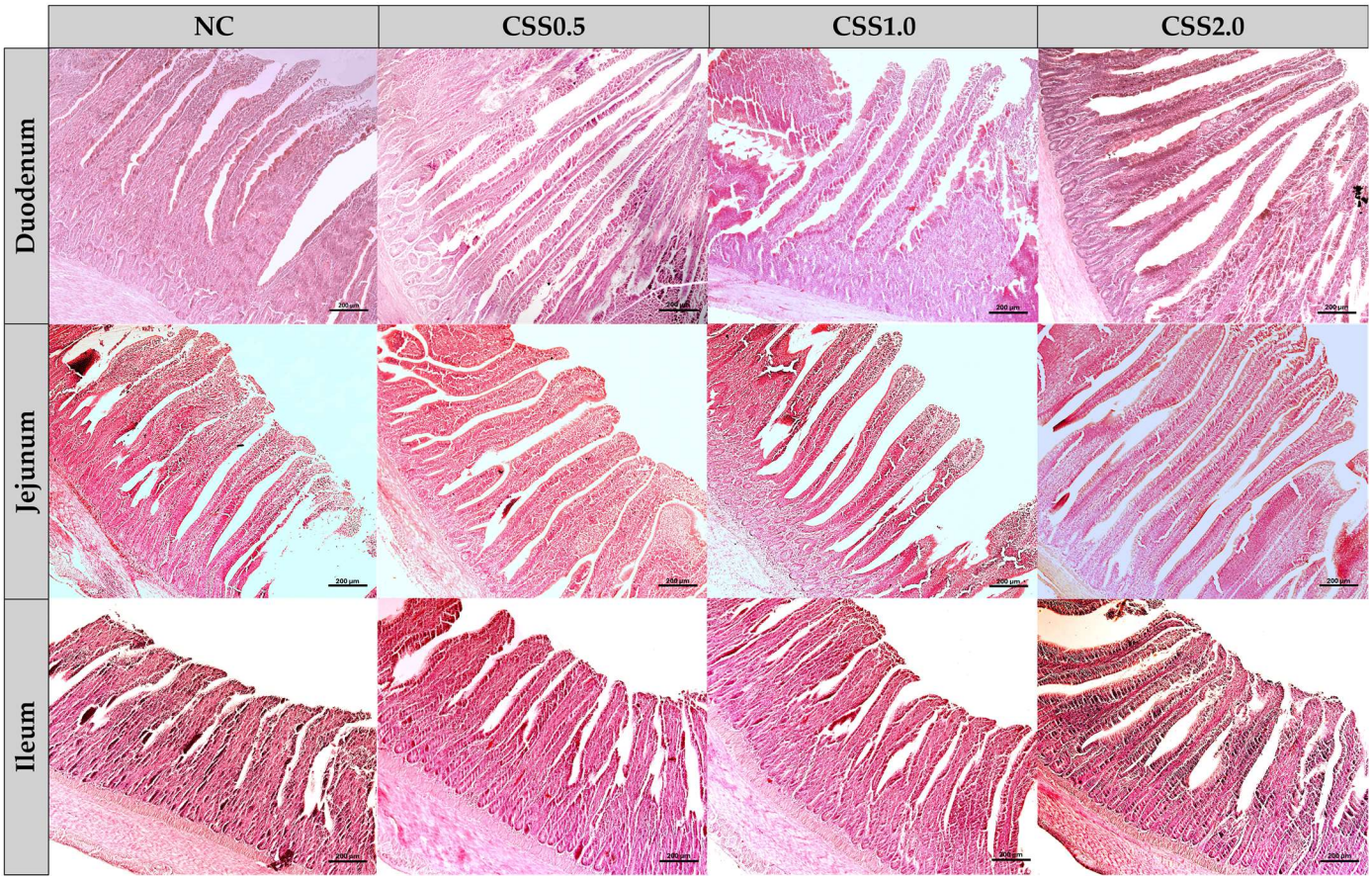

Figure 1. Histological representations of the small intestine of broiler chickens: NC: basal diet; CSS0.5: basal diet with coffee silverskin at 0.5 g/kg; CSS1.0: basal diet with coffee silverskin at 1.0 g/kg; CSS2.0: basal diet with coffee silverskin at 2.0 g/kg. Magnification was 10× the objective lens. Scale bars represent 200 μm.

4. Discussion

Coffee silverskin is a by-product of coffee roasting that has gained increasing attention due to its richness in bioactive compounds [3]. Coffee silverskin contains phenolic compounds, caffeine, and chlorogenic acids, which have been associated with antioxidant, anti-inflammatory, and lipid-modulating effects [5,10]. In poultry production, the search for natural feed ingredients has highlighted the potential role of dietary antioxidants in improving growth performance and gut health.

The significant peak in ADFI observed at the 0.5 g/kg inclusion level (91.57 g/d; $p < 0.001$) suggests a sensory optimum where aromatic volatiles from the coffee roasting process act as an appetitive stimulus. Conversely, the numerical reduction in intake at the 2.0 g/kg level (81.10 g/d) may reflect a dose-dependent increase in bitter-tasting alkaloids, such as caffeine (1440.40 mg/100 g in raw CSS), which—while not aversive—may subtly temper the voluntary intake stimulation compared to lower inclusion rates. Dietary supplementation with 2.0 g/kg of CSS improved broiler growth performance by increasing body weight, average daily gain, and feed efficiency. These findings indicate that CSS may serve as a functional feed additive with potential applications in livestock production [7,14]. The growth-promoting effects are attributable to the rich bioactive profile of CSS, particularly its polyphenols (e.g., flavonoids, gallic acid) [24]. These compounds likely enhance nutrient utilization by modulating digestive enzymes [25], improving gut morphology [26], and beneficially shifting the gut microbiota [27]. Our findings align with reports on other phenolic-rich additives, such as grape seed extract [28] dandelion extract [29], and coffee cherry pulp extract [30], that similarly enhance poultry growth. The dose-dependent response suggests an optimal inclusion level between 1.0 and 2.0 g/kg, although further investigation is required to refine this across different production phases and to account for source-specific variability in bioactive composition [31], as reported for other by-products like grape pomace [32].

Dietary CSS at 1.0–2.0 g/kg improved broiler carcass characteristics, increasing defeathered weight, carcass yield, and total meat percentage. Notably, there was an increased breast meat yield at the 2.0 g/kg inclusion level compared with the NC group, an effect on lean mass deposition consistent with reports on grape seed extract and resveratrol [28,33,34]. Crucially, these gains in carcass yield did not compromise meat quality, as pH, color, and drip loss remained stable across all treatments. This stability presents a significant advantage over other polyphenol sources like grape pomace and eucalyptus leaves, which have been reported to alter fat distribution and meat pH [35,36]. The favorable outcome may be associated with the unique bioactive profile of CSS [37], which appears to preserve myofibrillar integrity [38] without affecting organ weights—a safety profile also observed for additives like gallic acid [39].

Dietary CSS beneficially modulated the cecal microbiota in broilers, suppressing pathogenic *E. coli* and *Salmonella* sp. while promoting the growth of *Lactobacillus* sp. This effect may contribute indirectly through modulation of the gut microbial ecosystem. The enrichment of beneficial bacteria such as *Lactobacillus* sp. may inhibit pathogenic microorganisms via competitive exclusion, production of organic acids, and improvement of gut environmental conditions due to the phenolic compounds in CSS, which disrupt bacterial cell membrane integrity, leading to ion leakage and impaired virulence [40]. This mechanism—involving ATP depletion and inhibition of DNA gyrase [25]—is consistent with the action of other flavonoid-rich botanicals like thyme, oregano, and grape seed extract [41–45]. By fostering a healthier microbial balance, CSS may consequently enhance the intestine's absorptive capacity.

Dietary CSS enhanced small intestinal morphology, increasing VH and VH:CD—a key indicator of absorptive capacity. These architectural improvements, particularly at

1.0–2.0 g/kg CSS, are consistent with a conserved mechanism for plant-derived polyphenols [40,46]. Our results corroborate findings on grape pomace, which induced similar duodenal and jejunal adaptations [32], and align with the enhanced VH:CD ratios reported for guava and dandelion extracts [29,40,47]. The segment-specific variability we observed may reflect regional differences in polyphenol bioavailability or nutrient transporter expression [48].

Coffee silverskin improves intestinal morphology through two synergistic mechanisms: direct epithelial stimulation and indirect microbial modulation. First, its phenolic compounds, such as chlorogenic acid, likely promote enterocyte turnover via ERK/NF-κB signaling, a pathway also activated by grape seed polyphenols [48,49]. Second, CSS shifts the gut microbiota by suppressing pathogens like *E. coli* while enriching for beneficial Lactobacillus, which in turn mitigates intestinal inflammation and preserves epithelial integrity [40,46,50]. The different jejunal effects observed between CSS and tannin-rich grape pomace [51] likely stem from their distinct polyphenolic profiles, particularly the predominance of caffeine derivatives in CSS.

5. Conclusions

Dietary supplementation with CSS is an effective strategy to improve broiler production efficiency. At levels of 0.5–2.0 g/kg, CSS enhanced growth performance, improved carcass yield, and beneficially modulated the cecal microbiota by suppressing pathogens while promoting *Lactobacillus* sp. Crucially, these benefits were achieved without compromising meat quality parameters. Therefore, CSS represents a promising and sustainable functional feed additive for the poultry industry, with future research needed to optimize dosage across different production phases.

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Informed Consent Statement: Not applicable.

Data Availability Statement: Data are available on request due to restrictions, e.g., privacy or ethical restrictions. The data presented in this study are available on request from the corresponding author. The data are not publicly available due to the regulations of the Ministry of Higher Education, Science, Research, and Innovation.

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