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Original Research Article

Effect of Dietary Supplementation With Tomato By-Products on Zootechnical Performance and Biochemical Parameters in Broilers (*Gallus gallus*)

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ABSTRACT

In Morocco, tomatoes are one of the most produced crops, and the processing industry generates a significant quantity of by-products rich in bioactive compounds that are often undervalued. Therefore, this study sought to valorize these by-products by evaluating the effect of dietary supplementation with tomato by-products on the zootechnical performance and biochemical parameters of broiler chickens (*Gallus gallus*). A total of 250 one-day-old Cobb 500 chicks were randomized and assigned to 10 groups receiving industrial poultry feed supplemented with tomato by-products at 5%, 10%, and 15% (w/w) during different growth stages (beginning and/or growth) over 40 days. A control group was maintained on the standard diets without additions. Supplementation with tomato by-products affected various parameters depending on the supplementation percentage and stage. Specifically, compared to meat from control group, meat from experimental groups exhibited statistically significant increases in ash content (1.34±0.13 to 1.59±0.18 vs. 1.21±0.11 g/100 g; mean ± SD) and statistically significant decreases in protein content (17.36±0.52 to 21.78±0.84 vs. 22.84±1.08 g/100 g). Additionally, statistically significant improvements in colour differences were observed in meat from experimental groups. Furthermore, chicks maintained on feed supplemented with 5% by-products at the beginning stage demonstrated enhanced zootechnical performance (compared to the control), as evidenced by statistically significant potentiation of Live Weights, Average Daily Gain, and the Consumption Index. Thus, dietary supplementation with tomato by-products positively influenced zootechnical performance and most biochemical parameters of chicken meat, except for protein content. These findings suggest that tomato by-products can serve as a cost-effective supplement.

Keywords: Broiler chicks, Tomato by-products, Valorization, Performance.

Introduction

In recent years, poultry production has achieved phenomenal gains in the efficient and economical production of high-quality and safe chicken meat and eggs.[1] A major factor in this success is the use of high-quality ingredients in poultry feeding.[2,3] The most important agronomic products that are commonly used in poultry feed are maize and soybean meal.[4,5] These products have been shown to have nutritional value for chickens.[5,6] These natural products contain a wide range of nutritive and chemical constituents that help chicks increase yield and body performance.[7–9] Many fruits and vegetables or their by-products also are used for poultry feed.[10–12] Currently, farmers use natural by-products, such as fruit and vegetable waste, to feed animals,[13] including broiler chicks, rabbits, goats, and sheep.[14] These by-products have been shown to improve the yield and productivity of animals maintained on these supplemented diets.[15,16]

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Tomato (*Solanum lycopersicum*) processing by-products account for 5 to 19% of the total weight of tomatoes.[17] These material consist mainly of skins and seeds.[18,19] A large proportion of tomatoes is consumed after industrial processing,[20] which generates a significant quantity of by-products.[21,22] These tomato by-products are rich in valuable biomolecules,[23–25] but are often undervalued.[26] Typically, these materials are discarded due to management difficulties, although in some cases, the by-products are utilized in agriculture or as livestock feed. Morocco is the leading tomato-growing country in North Africa and one of the largest growers worldwide, with tomato production in Morocco amounting to approximately 1.311 million tons in 2021 and 1.388 million tons in 2022.[27] Additionally, Morocco is the third-largest producer (after Egypt and South Africa) of chicken meat in Africa.[27] In 2023, Morocco produced 560 000 tons of poultry meat.[28] This level currently fulfills all domestic poultry meat requirements, and accounts for 52% (by weight) of the total meat consumption in the country. Notably, increases in poultry production would improve Morocco's food security in terms of animal protein, given poultry's relatively low price compared to other sources of animal protein.[29] The relevance of this study lies in the strategic use of available resources. Specifically, the production and processing of large quantities of tomatoes in Morocco provide a substantial amount of by-products that might be reused as poultry feed. Supplementation would not only improve the nutritional value of the feed, but also support the poultry industry, which plays a crucial role in national food security. The incorporation of tomato by-products into poultry diets therefore would be expected to promote sustainability, economic efficiency, and food security.
This study sought to assess the effect of dietary supplementation with tomato by-products on biochemical parameters and zootechnical performance in broiler chicken, a breed widely consumed in Morocco. This research focused on tomatoes because their by-products contain a wide range of bioactive substances that may improve chicken

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productivity and the nutritional value of the resulting chicken meat. The by-products used were derived from the industrial processing of three varieties of tomato: Ercole, Galilea, and Advance. These varieties are widely used by tomato concentrate producers. These tomato by-products consist of seeds and skins, which usually are discarded following processing, but are an interesting source of bioactive components such as lycopene, dietary fiber and polyphenols. This study was expected to have two impacts: economic impacts, concerning the valorization of by-products from the tomato processing industry as an ingredient in poultry feed; and nutritional impacts, concerning the improvement of the Moroccan consumer's diet by offering poultry products (poultry meat) with increased nutritional value.

Materials and Methods

Biological materials
Animal material
In this study, 250 one-day-old chicks of the Cobb 500 strain were procured from the DELTAVI hatchery, located in M'Nassra, Kenitra, Morocco. The chicks were weighed and randomized for allocation into 10 groups, each of which was maintained on a different diet for an experimental period of 40 days. The animal-use protocol employed in this research met all relevant ethical standards, as evidenced by compliance with the principles of the European Community (EC) Directive 2010/63/EEC regarding the protection of animals used for experimental and other scientific purposes; the Council Directive 2007/43/EC concerning stocking density, lighting, and vaccination; and the relevant Moroccan laws regarding the sanitary protection of poultry farms and production control.

Plant material
The standard diets were supplied by the "Société Nouvelle de Volailles" in Temara, Morocco, a unit authorized by the National Office of Food Safety. The diets consisted of cereals, oilseed cake, fish meal, agro-industrial by-products (vegetable oils, molasses, etc.), and mineral and vitamin supplements. The feed given during the beginning stage (Day 1 to 21 post-hatch) contained 21.5% protein, 2.5% fat, 6% ash, 6% crude fiber, 0.6% phosphorus, 1.05% calcium, 1000000 IU / 100 kg of vitamin A, 150000 IU / 100 kg of vitamin D, and 2000 IU / 100 kg of vitamin E. The feed given during the growth stage (Day 22 to 40 post-hatch) contained 18.5% protein, 2.5% fat, 6% ash, 6% crude fiber, 0.6% phosphorus, 1.05% calcium, 800000 IU / 100 kg of vitamin A, 120000 IU / 100 kg of vitamin D, and 2000 IU / 100 kg of vitamin E. The water content of these feeds was 13%. Tomato by-products were obtained from "Exta Nouvelle" company, located in Sidi Allal Tazi, Morocco (34°33'19''N, 6°15'13''W), which specializes in the production of tomato concentrate. The by-products were collected in August of the 2023 production campaign and derived from the industrial processing of three tomato varieties: Ercole, Galilea, and Advance. These by-products, consisting mainly of skins and seeds, were sun-dried for 48 hours, then ground and packed in food-grade bags until use. The tomato by-products used in this study contained 0.93% NaCl, 5.11% ash, 6.1% fat, 15.4% protein, 35.1% fiber, 4.1 g/kg of calcium, 28.13 mg/kg of zinc, 0.42 mg/kg of phosphorus, 30.15 mg/kg of manganese, and 0.15 mg/kg of magnesium; water content was 8.02%.

Ethics approval for the research
The animal-use protocol employed in this research met all relevant ethical standards, as evidenced by compliance with the principles of the European Community (EC) Directive 2010/63/EEC regarding the protection of animals used for experimental and other scientific purposes; the Council Directive 2007/43/EC concerning stocking density, lighting, and vaccination; and the relevant Moroccan laws regarding the sanitary protection of poultry farms and production control, in particular Law No. 49-99, Decree No. 2-04-684, Order of the Minister of Agriculture, Rural Development, and Maritime Fisheries No. 2127-05, and Order of the Minister of Agriculture, Rural Development, and Maritime Fisheries No. 2125-05.

Experiment
The experiment was conducted at the poultry house of the Royal Institute of Specialized Technicians in Livestock of Fouarat, based in Kenitra, Morocco.
The chicks were divided into ten groups and maintained on poultry feed supplemented with different levels of tomato by-products, as shown in Table 1. Control chicks were maintained on unsupplemented poultry feed.

Table 1: Percentages of tomato by-products used for supplementation during the beginning and/or growth stages

Group No.	Supplementation during the beginning (from the 1st to the 21st day) (% w/w)	Supplementation during the growt (from the 22nd to t 40th day) (% w/w
Control	**0**	**0**
1	5	0
2	0	5
3	5	5
4	10	0
5	0	10
6	10	10
7	15	0
8	0	15
9	15	15

The chicks (control and experimental) were vaccinated against Newcastle disease,[30] infectious bronchitis, and infectious bursal disease (also referred to as Gumboro disease).[31]
After growth (at 40 days), chickens were weighed using a calibrated scale and then four randomly selected chickens per group were euthanized in the institute's slaughterhouse. Carcass weight was recorded for each chick. Then, the broiler chicks were dissected, and the mass of each body section (meat, offal, etc.) was recorded. The flesh samples were stored at -18 °C pending analysis.
Measurement of the zootechnical performance of chickens
In this study, several zootechnical parameters, including live weight (LW), average daily weight gain (ADG), and consumption index (CI), were determined in both control and experimental broiler chicks.
The ADG was calculated according to Equation 1:

$$Average\ Daily\ Gain = \frac{mass_f - mass_b}{t} \qquad \text{------------ (1)}$$

Where $mass_f$ is the mass in grams at the end of a period, $mass_b$ is the mass in grams at the beginning of a period, and t is the time interval (in days) between the measurements.
The CI was calculated according to Equation 2:

$$Consumption\ Index = \frac{quantity\ of consumedfeed\ (Kg)}{total\ live\ weight\ (Kg)} \qquad \text{---------- (2)}$$

Calculation of the yield
The yields of the different parts of chicken (meat and offal) were normalized to the live weight and to the carcass weight.
Measurement of biochemical parameters of chicken meat
The following parameters were analyzed for each chicken sample (control and experimental): salt, ash, carbohydrate, fat, protein content, and energy.
Parameters were determined as follows: salt (sodium chloride) content according to the Mohr Method;[32] ash content according to International Organization for Standardization (ISO) 936:2019;[33] carbohydrate content using ultraviolet (UV) spectrophotometry;[34] fat content according to ISO 1443:1973;[35] protein content according to ISO 1871:2011;[36] and energy values by Atwater factors.[37]

Measurement of the biochemical parameters of the supplement
The following parameters were analyzed in the dried tomato by-products used as feed supplements: ash, moisture, fat, protein content, fiber, and minerals (sodium chloride, calcium, zinc, phosphorus, magnesium, and manganese).

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Parameters were determined as follows: ash according to ISO 5984:2022;[38] moisture according to AOAC (formerly the Association of Official Agricultural Chemists) Official Method 930.15;[39] fat according to ISO 6492:1999;[40] protein content according to ISO 5983-1:2005[41]; fiber according to ISO 6865:2000;[42] salt content (sodium chloride) according to the Mohr Method; calcium according to ISO 6490-1:1985;[43] and other minerals (zinc, phosphorus, magnesium, and manganese) by inductively coupled plasma atomic emission spectroscopy (ICP-AES).[44]

Measurement of colour

Colour was determined based on the ‘‘Commission Internationale de l´Eclairage’’ coordinates L* (lightness), a* (redness), and b* (yellowness) (CIELAB) colour model.[45] The colour space parameters L*, a*, and b* were measured by the reflectance method using a KONICA MINOLTA Chroma Meter CR-5 colourimeter using a 30-mm-diameter aperture. Each data point (L*, a*, b*) represents the mean of three replicates that were measured at randomly selected sites on the breasts, legs, and skin. Based on the above parameters, the dE (colour difference), C* (chroma), h° (hue angle), and YI (yellow index) values were calculated.

Chroma characterizes the saturation or vividness of colour and was calculated according to Equation 3:

$$C*=\sqrt{a^{*2}+b^{*2}}$$

The hue angle (h°) indicates the degree of the dominant spectral components (red, green, and blue). The value of h° ranges between 0 and 360, and was calculated according to Equation 4:

$$h^{\circ}=tan^{-1}(\frac{a^{*}}{b^{*}})$$

The yellow index is a colour measurement related to the browning index and was calculated according to Equation 5:

$$YI=142.86\,(\frac{b*}{L*})$$

The colour difference was calculated according to Equation 6:

$$dE=\sqrt{L_0^{*}*-L^{*})^2+(a_0^{*}-a^{*})^2+(b_0^{*}-b^{*})^2}$$

Statistical analysis

All of the data were analyzed for normality and homogeneity of variance using the Kolmogorov–Smirnov test. Data are presented as the mean ± SD for each variable. The comparison of means among the control and experimental groups maintained on feed supplemented with 5%, 10%, and 15% by-products during the beginning, growth, and beginning-growth stages was performed with the multiple range test. To evaluate the correlation of the studied parameters, a correlation matrix based on Spearman rank correlation coefficients was used. p-values of <0.05 were considered statistically significant.

Results and Discussion

Comparison of biochemical parameters

Table 2 presents the effects of dietary supplementation with tomato by-products on the biochemical characteristics of broiler chicken meat (breast and leg). Analysis of the data revealed a variable effect of the percentage of supplement used, and of the stage at which supplementation was provided, on the parameters studied in the broiler chicks.

The supplementation of broiler chicks' diet with 5% tomato by-products significantly increased the salt content (sodium chloride) in all stages compared to the control (0.10±0.01 g/100g; mean ± SD), with nominally higher values observed for supplementation during both the beginning stage (0.22±0.02 g/100 g) and growth stage (0.19±0.03 g/100 g). Furthermore, the supplementation of broiler chick's diet with 10% tomato by-products resulted in increased salt content only when provided during the beginning stage (0.20±0.03 g/100 g); in contrast, supplementation with 10% by-products during the growth or beginning-growth stages resulted in salt levels that were statistically indistinguishable from those of the control. Moreover, the groups supplemented with 15% during the beginning stage and growth stage, showed a significant increase in salt content (0.18±0.05 and 0.17±0.02 g/100 g, respectively) compared to the control, while during the beginning-growth stages, the value was comparable to the control.

The ash content of the chicken meat also was influenced by supplementation. The supplementation of broiler chicks' diet with 5% tomato by-products (at any stage) resulted in significant increases in ash content compared to the control (1.21±0.11), and the strong increases were recorded for chickens maintained on supplemented feed during both the beginning stage (1.59±0.18 g/100 g) and growth stage (1.52±0.15 g/100 g). Furthermore, the supplementation of broiler chicks' diet with 10% tomato by-products (at any stage) provided significant increases in ash content compared to the control, with nominally higher values observed for supplementation during both the growth stage (1.50±0.16 g/100 g) and beginning-growth stages (1.53±0.17 g/100 g) compared to supplementation at the beginning stage only (1.27±0.12 g/100 g). Similarly, the groups maintained on feed supplemented with 15% by-products (at any stage) showed significant increases in the amount of ash compared to the control.

The supplementation of broiler chicks' diet with 5% tomato by-products (at any stage) also resulted in significant increases in fat content, with the nominally largest increases (6.10±0.95 g/100 g) observed in chickens provided with supplementation during the growth stage. Furthermore, the supplementation of broiler chicks' diet with 10% tomato by-products (at any stage) resulted in significant increases in fat content compared to the control, with the nominally largest increases (6.21±0.94 g/100 g) observed in chickens provided with supplementation during the beginning stage. In contrast, meat from groups maintained on feed supplemented with 15% by-products (at any stage) exhibited fat content that was statistically indistinguishable from that observed in the control group.

The protein content in each of the groups maintained on supplemented feed was significantly lower than that in the control. The nominally lowest protein content was observed in the groups maintained on feed supplemented with 10% tomato by-products, particularly during the growth stage (17.36±0.52 g/100 g).

Carbohydrate levels were significantly increased (compared to the control) in chickens receiving feed supplemented with 5% tomato by-products during the beginning stage (0.50±0.03 vs; 0.40±0.04 g/100 g). In contrast, carbohydrate levels in chickens maintained with 5% tomato by-product supplementation during the growth and beginning-growth stages were statistically indistinguishable from that of the control. Similarly, the supplementation of broiler chicks' feed with 10% tomato by-products (at any stage) did not provide statistically significant increases in carbohydrate content (compared to the control), instead resulting in a nominal decrease (0.12±0.00 g/100 g) (compared to control) in chickens receiving supplementation during the growth stage. On the other hand, supplementation of broiler chicks' diet with 15% tomato by-products (at any stage) resulted in significant increases in carbohydrate levels compared to the control; the nominally largest effect was seen for supplementation during the beginning-growth stages (0.62±0.01 g/100 g).

In terms of energy, distinct effects were observed in broilers maintained on feed supplemented with various amounts of tomato by-products. Compared to the control, chickens maintained on feed supplemented with 5% tomato byproducts at the beginning or beginning-growth stages showed significantly decreased energy; however, no significant difference (compared to control) was seen for 5% supplementation during the growth stage alone. In the groups supplemented with 10% or 15% tomato by-products, energy decreased significantly in all treatment stages (compared to the control).

This study showed that the supplementation of chick's diets with different percentages of tomato by-products resulted in significant changes in selected biochemical parameters, including increases in ash, fat, and carbohydrates, and decreases in protein content and energy. The changes in these parameters varied depending on the percentage of tomato by-products added. In a previous study, the effect of different percentages of dried tomato by-products added (0%, 10%, and 15%) on the fatty acid composition of poultry meat was tested. The results of that work showed that supplementation with tomato by-products significantly decreased the saturated fatty acid content in the abdominal fat and thigh, while and significantly increasing the levels of polyunsaturated fatty acid.[46] In another study, tomato meal was

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included at levels of 0, 3, 6, 9, and 12% in the diets of kampong chicken. That work revealed a significant increase in meat crude protein and a significant decrease in meat crude fat and cholesterol.[47] In addition, feed supplementation with lycopene, which is abundant in tomato by-products, was shown to reduce serum total cholesterol, triglycerides, and low-density lipoprotein levels in broilers.[48]

Comparison of the zootechnical parameters

The comparisons of live weight (LW), average daily gain (ADG), and consumption index (CI) among the control and experimental chicks are presented in Table 3. The LWs of broiler chicks showed variable results, with increases (relative to the controls) in the group provided with feed supplemented with 5% tomato by-products during the beginning stage. In contrast, the LWs of groups provided with feed supplemented with 5% by-products during the growth stage were statistically indistinguishable from the control; while those provided with feed supplemented with 5% by-products (during the beginning-growth stages) or with 10% and 15% by-products (during the beginning and beginning-growth stages) showed significant decreases in LW values compared to the control.

The ADGs of broiler chicks also showed variable results, with improvements in group provided with feed supplemented with 5% tomato by-products during the beginning stage. The pattern of significant changes (compared to the control) were largely consistent with those seen for the LWs.

The CIs of broiler chicks also showed variable results, with significant increases (compared to control) seen in groups provided with feed supplemented with 5% tomato by-products (during the beginning-growth stage) and with 10% and 15% tomato by-products (during the growth and beginning-growth stages, respectively). In contrast, a significant decrease in the CI value (compared to the control) was observed in the group provided with feed supplemented with 5% tomato by-products (during the beginning stage). The remaining groups exhibited CIs that were statistically indistinguishable from the control.

In a study, the assessment of zootechnical parameters in broiler maintained on tomato by-product-supplemented feed showed that, there was no significant difference between the experimental groups in terms of performance and carcass characteristics.[46] In another study, the effect of dried tomato waste meal on the growth performance of broiler chickens (Cobb 500) was tested. The authors used different percentages of supplementation, including 3, 6, 9, and 12%, during the starter and finishing stages. That work indicated that the inclusion in the diet of tomato waste meal at concentrations of up to 9% had no negative effect on the growth performance of broiler chickens.[49] In another study, the effect of tomato pomace (raw and fermented) on the growth performance of broiler chickens was tested. That work showed that the growth performance of chicks was not affected by dietary supplementation with 10 g/kg of tomato pomace or fermented tomato pomace.[50] In contrast, another study demonstrated that inclusion in the feed of graded levels of dried lemon (*Citrus aurantifulia*) attenuated both the weight and daily weight gain of chickens.[51] In yet another study, the effect on growth performance of supplementing the diet of broiler chickens with polyphenol-rich grape seeds was tested. Dietary supplementation with 20 g/kg of grape seed increased the final body weight and body weight gain in broiler chicks. This level of grape seed also improved the feed conversion ratio without affecting feed intake.[7] The effect of grape seeds (raw and fermented) on growth performance of broiler chickens also has been assessed. Weight and daily weight gain were significantly potentiated in chicks provided with feed supplemented with raw and fermented grape seed during the growth stage (22–42 days).[52] Other research demonstrated that the supplementation of broiler chicks' diets with processed rice bran potentiated feed consumption.[53] A similar study showed that feed consumption and the feed conversion ratio differed significantly different between chicks maintained on a standard diet and those maintained on a diet in which rice bran was partially replaced with yellow corn.[54] An additional investigation examined the synbiotic effects of *Moringa oleifera* extract and probiotics on the growth performance of broiler chickens. That work indicated that body weight, feed conversion ratio, and feed efficiency were significantly enhanced (compared to the control) in chickens maintained on feed supplemented with combinations of 1% to 2% *Moringa* extract and 1% to 2% probiotic.[55] The difference between the results of our study and those reported in the literature may have resulted from differences in the dietary supplement and the levels at which the material was supplemented. In fact, the amount of supplement used has been shown to be a determining factors in weight gain in experimental chickens, including broiler chicks.[56,57]

Comparison of colour

Table 4 presents the effects on the colour parameters (in broiler chicks) of dietary supplementation (at various stages) with tomato by-products. Our data analysis revealed a variable effect depending on the percentage of supplement used and the treatment stage of the broiler chicks.

Table 2: Comparison of biochemical parameters in meat from chickens maintained on feed supplemented with different levels of tomato by-products

ercentage of upplement		5%			10%			15%		
Stage	**C**	**B**	**G**	**B-G**	**B**	**G**	**B-G**	**B**	**G**	**B-G**
Salt (NaCl) (%)	0.10±0.01^{c}	0.22±0.02^{a}	0.19±0.03^{a}	0.17±0.01^{b}	0.20±0.03^{a}	0.13±0.01^{c}	0.14±0.07^{c}	0.18±0.05^{b}	0.17±0.02^{b}	0.13±0.0
Ash (%)	1.21±0.11^{c}	1.59±0.18^{a}	1.52±0.15^{a}	1.34±0.13^{b}	1.27±0.12^{b}	1.50±0.16^{a}	1.53±0.17^{a}	1.51±0.16^{a}	1.52±0.08^{a}	1.49±0.1
Fat (%)	5.11±0.75^{b}	4.89±0.65^{b}	6.10±0.95^{a}	5.64±0.79^{b}	6.21±0.94^{a}	5.79±0.77^{b}	4.92±0.68^{b}	4.87±0.69^{b}	5.09±0.71^{b}	5.150±0.7
Protein (%)	22.84±1.08^{a}	20.88±0.59^{c}	20.56±0.61^{c}	20.04±0.53^{c}	19.54±0.23^{d}	17.36±0.52^{e}	21.10±0.82^{b}	21.78±0.84^{b}	21.37±0.81^{b}	20.51±0.5
Total arbohydrate (%)	0.40±0.04^{c}	0.50±0.03^{b}	0.30±0.01^{c}	0.30±0.00^{c}	0.28±0.01^{c}	0.12±0.00^{d}	0.35±0.02^{c}	0.52±0.00^{b}	0.54±0.00^{b}	0.62±0.01
Energy (kJ)	584.15±12.03^{a}	544.39±8.24^{c}	580.32±11.22^{a}	554.46±9.88^{c}	566.71±9.65^{b}	511.39±7.88^{d}	546.69±6.74^{c}	559.29±10.01^{b}	560.80±14.10^{b}	549.76±8. 9^{c}

C: Control; B: Supplementation in the beginning stage; G: Supplementation in the growth stage; and B-G: Supplementation in the beginning and growth stages. Data represent mean ± SD (n=4). a, b, c, d, and e denote significant differences ($p < 0.05$), a>b>c>d>e.

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Table 3: Comparison of zootechnical parameters

Percentage of supplement		5%			10%			15%		
Stage	**C**	**B**	**G**	**B-G**	**B**	**G**	**B-G**	**B**	**G**	**B-G**
Live Weight (g)	2105±245^{b}	2265±155^{a}	2105±222^{b}	1937±227^{c}	2090±205^{b}	1985±237^{c}	1910±152^{c}	2060±122^{b}	1980±220^{c}	1960±298^{c}
Average Daily Gain (g/d)	52.8±6.2^{b}	56.9±3.9^{a}	52.8±5.6^{b}	48.5±5.8^{c}	52.4±5.2^{b}	49.7±6.0^{c}	49.5±3.8^{c}	47.8±3.1^{c}	51.6±5.6^{b}	49.1±7.6^{c}
Consumption Index	1.98±0.222^{b}	1.827±0.126^{c}	1.976±0.200^{b}	2.155±0.266^{a}	1.988±0.187^{b}	2.103±0.259^{a}	2.17±0.175^{a}	2.006±0.115	2.103±0.219^{a}	2.15±0.355^{a}

C: Control; B: Supplementation at the beginning stage; G: Supplementation at the growth stage; and B-G: Supplementation at the beginning and growth stages. Data represent mean ± SD (n=4). a, b, and c denote significant differences (p <0.05), a>b>c.

Table 4: Comparison of dE, C*, h°, and YI in chicken breast, leg, and skin between experimental and control groups

Percentage of supplement			5%			10%			15%		
Stage		**C**	**B**	**G**	**B-G**	**B**	**G**	**B-G**	**B**	**G**	**B-G**
	dE	0^{c}	3.7±0.94^{a}	2.26±1.17^{a}	1.84±1.46^{b}	3.8±2.15^{a}	3.03±0.72^{a}	2.89±1.16^{a}	2.19±0.77^{a}	2.99±1.14^{a}	2.98±1^{a}
	C*	18.62±0.8^{a}	17.89±0.7^{b}	17.48±0.96^{b}	18.13±0.96^{a}	19.26±2.44^{a}	18.2±1.15^{a}	16.97±0.8^{b}	19.76±1.09^{a}	17.10±0.98^{b}	18.67±1.76^{a}
	h°	63.1±1.57^{b}	67.86±2.93^{a}	63.06±4.02^{b}	64.65±3.94^{b}	66.78±2.03^{a}	66.59±1.79^{a}	66.56±1.51^{a}	64.88±1.54^{b}	67.45±3.21^{a}	65.17±3.09^{a}
Breast	YI	39.11±2.31^{a}	37.06±2.18^{b}	36.56±2.23^{c}	38.14±1.91^{b}	40.28±4.01^{a}	37.75±2.93^{b}	35.77±1.39^{c}	41.17±1.94^{a}	36.22±1.59^{c}	39.35±3.22^{b}
	dE	0^{c}	4.75±2.89^{a}	4.38±2.96^{a}	3.22±2.81^{b}	5.12±2.10^{a}	3.69±1.73^{b}	3.89±1.25^{b}	4.85±1.79^{a}	4.44±2.37^{a}	2.59±1.4^{b}
	C*	16.2±1.77^{a}	15.78±2.11^{a}	13.73±0.85^{b}	15.95±0.58^{a}	16.62±3.11^{a}	16.36±2.68^{a}	14.49±1.46^{b}	16.63±2.42^{a}	15.46±0.67^{a}	17.27±1.47^{a}
	h°	54.5±1.68^{b}	62.35±5.57^{a}	57.46±2.62^{b}	55.88±4.79^{c}	61.4±5.57^{a}	58.9±1.08^{a}	57.83±3.43^{b}	59.24±5.19^{a}	58.5±4.23^{a}	56.94±3.33^{b}
Leg	YI	33.10±2.9^{a}	33.23±4.57^{a}	27.77±2.2^{c}	31.91±1.08^{b}	34.36±6.87^{a}	34.05±4.87^{a}	29.93±3.34^{b}	35.18±4.37^{a}	30.86±1.84^{b}	35.41±2.44^{a}
	dE	0.00±0.00^{d}	3.06±1.45^{c}	2.61±0.19^{c}	7.08±4.38^{b}	4.78±2.49^{c}	5.46±1.79^{c}	4.82±2.49^{c}	4.24±1.81^{c}	11.58±3.35^{a}	4.64±0.47^{c}
	C*	17.57±0.00^{a}	18.73±1.69^{a}	18.29±0.20^{a}	17.66±3.19^{a}	19.44±4.91^{a}	20.20±1.72^{a}	20.27±0.69^{a}	17.93±2.30^{a}	19.75±2.84^{a}	14.28±0.28^{b}
	h°	79.07±0.00^{a}	78.52±3.21^{a}	80.25±6.10^{a}	79.78±4.32^{a}	80.36±5.09^{a}	78.82±6.38^{a}	73.77±4.48^{b}	79.97±10.83^{a}	72.20±8.25^{b}	85.07±2.62^{a}
Skin	YI	34.19±0.00^{b}	35.46±2.38^{a}	34.68±0.10^{b}	37.50±9.19^{a}	36.93±9.62^{a}	41.37±2.33^{a}	40.37±1.97^{a}	34.70±4.66^{b}	43.26±3.91^{a}	28.90±0.41^{b}

C: Control; B: Supplementation at the beginning stage; G: Supplementation at the growth stage; and B-G: Supplementation at the beginning and growth stages. dE: difference of colour; C*: chroma; h°: hue angle; and YI: yellowness index. Data represent mean ± SD (n=4). a, b, c, and d denote significant differences (p <0.05), a>b>c>d.

Breast

In chickens maintained on feed supplemented with tomato by-products (at various percentages and stages), breast meat exhibited the dietary supplementation of broiler chicks with different percentages significantly increases in the dE during compared to the control. In terms of comparison among all group, the greatest increase in dE was recorded in the groups maintained on feed supplemented with 10% and 15% by-products (at any stage), and in the groups maintained on feed supplemented with 5% by-products during the beginning and growth stages.

In terms of chroma, chickens maintained on feed supplemented with tomato by-products typically showed values that were statistically indistinguishable from the control with the exception of significant decreases in broilers maintained on feed supplemented with 5% by-products (during the beginning and growth stage), with 10% by-products (during the beginning-growth stages), or with 15% by-products (during the growth stage).

The recorded hue angle (h°) data showed variable results depending on the percentage of supplement used and the growth stage of the broiler chicks. In the group maintained on feed supplemented with 5% tomato by-products, significant increases (compared to control) were seen in h° with exposure during the beginning stage, and not with exposure during the growth and beginning-growth stages. Significant increases in h° (compared to the control) also were seen in groups maintained on feed supplemented with 10% by-products (at any stage) or with 15% by-products (at the growth or beginning-growth stages).

Similarly, the YI showed variable results. Compared to the control, chickens maintained on feed supplemented with 5% tomato by-products (at any stage) showed significant decreases in YI. Significant decreases (compared to the control) also were seen in chickens maintained on feed supplemented with 10% or 15% by-products during the growth and beginning-growth stages.

Leg

In leg meat, the values of the colour parameters were variable among the groups provided with supplementation with different percentages of tomato by-products. For all percentages of tomato by-products, dietary supplementation (at any stage) resulted in significant increases in dE compared to the control. The nominally largest increases in dE were recorded in the groups maintained on feed supplemented with 10% by-

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products (during the beginning stage) and with 15% by-products (during the beginning and growth stages); among those maintained on feed supplemented with 5% tomato by-products, nominally larger effects were seen during the beginning and growth stages.

In terms of the chroma in leg meat, values were statistically indistinguishable from the control, with the exception of significant decreases in chickens maintained on feed supplemented with 5% by-products (during the growth stage) and 10% by-products (during the beginning-growth stage).

The recorded h° data for leg meat showed variable results depending on the percentage of supplement used and the growth stage of the broiler chicks. Notably, compared to the control, h° was significantly increased in chickens maintained on feed supplemented with 5% by-products (during the beginning stage), and with 10% or 15% by-product (during both the beginning stage and growth stage).

In terms of the YI of the leg meat, values were statistically indistinguishable from the control, with the exception of significant decreases in broilers maintained on feed supplemented with 5% or 15% by-products (during the growth stage) and with 5% or 10% by-products (during the beginning-growth stages).

Skin

In the skin, the dE values were significantly elevated (compared to the control) in all groups maintained on feed supplemented with tomato by-products (at any percentage and any stage). The dE value in the broiler chicks group maintained on feed supplemented with 15% by-products during the growth stage was significantly elevated compared to all other experimental groups (11.58±3.35).

Except for the broiler chicks group maintained on feed supplemented with 15% by-products during the beginning-growth stages that showed a significant decrease in chroma value (14.28±0.28), all experimental chicks showed skin chroma values similar to the control (17.57±0.00).

The skin h° values in the experimental chickens were statistically indistinguishable from those in the control (79.07±0.00°), with the exception of significant decreases (compared to the control) for chicks maintained on feed supplemented with 10% by-products during the beginning-growth stages (73.77±4.48°) and with 15% by-products during the growth stage (72.20±8.25°).

Significant increases in the skin YI (compared to the control) were observed in chicks provided with feed supplemented with 5% by-products (during the beginning and beginning-growth stages), with 10% by-products (at any stage), and with 15% by-products (during growth stage).

Therefore, our data indicated that the dE of the breast, thigh, and skin of broiler chicks were increased by dietary supplementation with tomato by-products. For comparison, we note that a previous study reported that chickens maintained on a basal (soybean-based) diet supplemented with 20% expeller press canola meal exhibited significant increases (compared to control chickens) in skin yellowness, breast chroma values, skin redness, and hue angle values.[58] These results are in agreement with the present data. We hypothesize that the observed improvement in colour and quality parameters in broiler chicks provided with feed supplemented with tomato by-products reflects the lycopene and β-carotene content of the supplementation.[59,60]

Comparison of yield

Meat yield relative to live weight and carcass weight

The effects of tomato by-products on the meat yield normalized to the LW and carcass weight of broilers are presented in Table 5. The comparison between the control group and those maintained on feed supplemented with different percentages of the tomato by-products showed different results depending on the percentage used and stage.

In terms of LW-normalized yield, the value was significantly increased (compared to the control) only in broilers provided with supplementation with 15% by-products during the growth stage, and significantly decreased in chicks provided with supplementation with 5% by-products during the beginning stage and growth stage. Similarly, the carcass weight-normalized yield we significantly elevated (compared to the control) in broilers provided with supplementation with 15% during the growth stage, and significantly decreased in chicks provided with supplementation with 10% by-products during the growth stage and 15% by-products during the beginning stage.

Chicken offal yield relative to live weight and carcass weight

The effects of supplementation with tomato by-products on the offal yield normalized to the LW and carcass weight of broiler chicks are presented in Table 6. The comparison between the control and those supplemented with different percentages of the tomato by-products showed different results depending on the percentage used and the stage.

The LW-normalized offal yield was significantly increased (compared to the control) in groups provided with supplementation with 10% by-products during the beginning stage and the beginning-growth stages, but significantly decreased in the majority of the other experimental groups. In terms of the carcass weight-normalized offal yield, the values were significantly changed (increased, compared to the control) only for chickens provided with supplementation with 5% and 10% tomato by-products during the beginning stage and with 10% and 15% tomato by-products during the beginning-growth stages.

These yield data are contradictory to previously reported results showing that the inclusion of tomato waste meal at up to 9% in the diet had no negative effects on the carcass characteristics of broiler chickens.[49] In another study, the effect of tomato on the carcass of kampong chicken was tested, showing that the addition of 12% tomato meal to the diet enhanced carcass, thigh, breast meat, and slaughter weights.[47]

Correlation between zootechnical performance, biochemical parameters, and total supplementation

Correlations among the studied parameters were assessed; the results of these analyses are presented in Table 7. A positive and significant correlation was observed between ADG and both CI and weight. In contrast, a negative and significant correlation was observed between fat and ash, carbohydrates, and protein content. However, we were unable to detect a significant correlation between the total supplementation and the parameters studied, given the lack of sufficient factor levels.

Table 5: Meat yield in relation to live weight and carcass weight

Percentage of supplement		5%			10%			15%		
Stages	**C**	**B**	**G**	**B-G**	**B**	**G**	**B-G**	**B**	**G**	**B-G**
Yield relative to live weight (%)	37.01±1.73^{b}	35.65±2.74^{c}	36.23±2.27^{c}	36.87±1.36^{b}	38.81±2.49^{b}	37.18±0.74^{b}	37.27±0.93^{b}	36.99±2.87^{b}	43.12±4.06^{a}	37.88±1.45^{b}
Yield relative to carcass weight (%)	58.62±2.56^{b}	57.34±2.61^{b}	57.12±3.05^{b}	58.7±1.29^{b}	59.19±0.82^{b}	56.50±2.58^{c}	57.79±0.94^{b}	56.96±2.88^{c}	66.69±7.83^{a}	57.86±2.23^{b}

C: Control; B: Supplementation at the beginning stage; G: Supplementation at the growth stage; and B-G: Supplementation at the beginning and growth stages. Data represent mean ± SD (n=10). a, b, and c denote significant differences ($p < 0.05$), a>b>c.

Table 6: Chicken offal yield relative to live weight and carcass weight

Percentage of supplement		5%			10%			15%		
Stage	**C**	**B**	**G**	**B-G**	**B**	**G**	**B-G**	**B**	**G**	**B-G**
Yield relative to live	3.93±0.6	3.64±0.1	3.34±0.3	3.51±0.1	4.01±0.3	3.55±0.3	4.14±0.2	3.30±0.3	3.72±0.0	3.89±0.0
weight (%)	3^{b}	3^{c}	5^{c}	1^{c}	8^{a}	1^{c}	6^{a}	5^{c}	7^{b}	9^{b}
Yield relative to carcass	6.23±1.0	5.87±0.2	5.26±0.4	5.59±0.3	6.12±0.3	5.37±0.3	6.42±0.3	5.09±0.5	5.75±0.2	5.94±0.1
weight (%)	8^{a}	1^{a}	8^{b}	2^{b}	6^{a}	2^{b}	3^{a}	2^{c}	0^{b}	3^{a}

C: Control; B: Supplementation at the beginning stage; G: Supplementation at the growth stage; and B-G: Supplementation at the beginning and growth stages. Data represent mean ± SD (n=4). a, b, and c denote significant differences ($p < 0.05$), a>b>c.

Table 7: Correlation between the studied parameters based on Spearman coefficients

	ADG	ASH	CARB	CI	EN	FAT	LW	PR	SALT	T. S
ADG	-									
ASH	0.0515	-								
CARB	0.0279	0.2409*	-							
CI	-0.9967***	-0.0654	-0.0296	-						
EN	0.0337	-0.4559***	0.0426	-0.0312	-					
FAT	-0.057	-0.5106***	-0.6748***	0.0619	0.2727***	-				
LW	0.9967***	0.0654	0.0296	-1***	0.0312	-0.0619	-			
PR	0.0478	0.1945	0.6261***	-0.0484	0.4061***	-0.7333***	0.0484	-		
SALT	0.2362*	0.4251***	0.1009	-0.2458*	0.0488	-0.0122	0.2458*	-0.1281	-	
T. S	-0.3015**	0.1796	0.4304***	0.2759**	-0.3766***	-0.2531*	-0.2759**	-0.0556	-0.2081*	-

*$p < 0.05$, ** $p < 0.01$, ***$p < 0.001$. PR: Proteins, Carb: Carbohydrates, Energy: EN, LW: Live Weight, ADG: Average Daily Gain, CI: Consumption Index, T. S: Total supplementation with tomato by-products over the experiment.

Conclusion

The results showed the variable effects of feed supplementation with tomato by-products on broiler chicks, depending on the percentage of supplementation, treatment stage, and the measured parameters. Increased values of the main study parameters were recorded following feed supplementation with 5% tomato by-products during the beginning stage. These new data are expected to be highly relevant for the production of broiler chicks and for field agriculture in Morocco, a country that is considered one of the most important producers of tomatoes in North Africa. Notably, to our knowledge, no Moroccan study to date has reported the use of tomatoes or their by-products in poultry production. Our work provides valuable new data describing the ability of tomato by-products to improve biochemical parameters as well as yield. We suggest that these results suggest that feed manufacturers should incorporate tomato by-products in the formulation of poultry diets. However, more research will be needed to investigate the effects of tomatoes on other physiological and biological parameters of chicks.

Conflict of Interest

The authors declare no conflict of interest.

Authors' Declaration

The authors hereby declare that the work presented in this article is original and that any liability for claims relating to the content of this article will be borne by them.

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