The effects of paulownia (Paulownia tomentosa) leaf extract enriched diets on meat quality, sensory attributes, and the potential economic impact of broilers

Shimaa A. Sakra, Huda A. EL-Emama, Mohammed A. E. Naiel, Noha M. Waheda, Hanan A. Zaher, Mohamed Mohamed Soliman, Mustafa Shukry, Abdelrazeq M. Shehata, Adil Alkhedaide, and Mona M. Elghareeb

Department of Husbandry and Development of Animal Wealth, Faculty of Veterinary Medicine, Mansoura University, Mansoura, Egypt; Department of Animal Production, Faculty of Agriculture, Zagazig University, Zagazig, Egypt; Food Hygiene and Control Department, Faculty of Veterinary Medicine, Mansoura University, Mansoura, Egypt; Clinical Laboratory Sciences Department, Turabah University College, Taif University, Taif, Saudi Arabia; Physiology Department, Faculty of Veterinary Medicine, Kafrelsheikh University, Kafrelsheikh, Egypt; Department of Animal Production, Faculty of Agriculture, Al-Azhar University, Nasr City, Cairo, Egypt; Department of Dairy Science and Food Technology, Institute of Agricultural Sciences, Banaras Hindu University, Varanasi, Uttar Pradesh, India; Physiology Department, Faculty of Veterinary Medicine, Mansoura University, Mansoura, Egypt

ABSTRACT

The present study was conducted to assess the effect of paulownia (Paulownia tomentosa) leaf extract (PLE) enriched diets on the quality of meat and the economic efficiency of broiler chickens. A total of 180 one-day-old male chicks (Cobb) were randomly assigned to four treatments with five replications each (9 birds per replicate). The chickens were fed corn-soybean-based diets supplemented with different levels of PLE (0, 0.1, 0.3, and 0.5 g kg\(^{-1}\)) for 42 days. The results showed that the inclusion of up to 0.5 g kg\(^{-1}\) PLE in the diet of broiler chickens significantly improved the live body weight, carcase weight, and carcase components (liver, heart, and gizzard) weights compared to the control group \((P < 0.05)\). Enriched broiler diets with 0.5 g kg\(^{-1}\) of PLE significantly reduced collagen and lipid content as well as increased total protein levels in both breast and thigh muscle compared to the un-supplemented group \((P < 0.001)\). Subjective evaluation of the breast meat showed a significant linear improvement in flavour and juiciness of meat samples from birds fed with dietary PLE in a dose-dependent manner \((P < 0.05)\). Supplementation with different levels of PLE significantly improved the sensory attributes (flavour, tenderness, juiciness, and overall acceptability) of thigh meat in a dose-dependent manner (linear; \(P < 0.05\)). Total potential return and net profit were significantly increased in all groups fed PLE compared to the control group. Birds that received PLE-supplemented diets at a level of 0.5 g kg\(^{-1}\) had the highest economic efficiency \((P < 0.05)\). Conclusively, supplementation with 0.5 g PLE/kg in broiler diets could improve meat quality and economic efficiency.

HIGHLIGHTS

- Enriched broiler diets with 0.5 g paulownia leaf extract significantly enhanced carcase measurements.
- Supplemented broiler diets with 0.5 g PLE significantly enhanced the meat quality and sensory attributes of thigh meat.
- Birds fed PLE-supplemented diets at a level of 0.5 g/kg had the highest economic efficiency.

Introduction

Meat quality and consistency are important in ensuring consumer satisfaction (Yang et al. 2020). In parallel to expanding meat consumption, consumer interest in healthy food is growing internationally, as is the desire for high-quality and safe products with longer shelf life (Abo Ghanima et al. 2020; Suliman et al. 2021). The quality of meat products can be classified into three major groups: a) quality traits related to meat appearance (such as drip or purge loss, colour, and texture); b) quality traits related to consumption (such as tenderness, juiciness, succulence, and flavors); and c) quality traits related to safety, high nutritional value, animal management, market price, ethics, product...
packaging, brand, and source of meat products (Arif et al. 2020; Hussein et al. 2020).

Several recent studies have shown that bird nutrition has a substantial influence on the safety and quality of meat products (Godfray et al. 2018; Abou-Elkhair et al. 2020; Dosoky et al. 2021). The poultry industry uses antibiotics to promote meat production via improved feed conversion, stimulate growth and prevented infectious diseases (Seidavi et al. 2022). Although present data suggest that antibiotic residues in meat have no direct influence on human health, the hazards of antibiotic-resistant bacteria developing in food animals present potential risks to consumer health (Barbosa and Levy 2000). Consequently, more emphasis is being placed on the raising of birds without using synthetic antioxidants, antibiotics, or hormones (Mir et al. 2017b). Herbal extracts such as Thymus vulgaris L., Ocimum gratissimum L., Origanum L., Carum copticum L., Satureja L., and Oliveria decumbens can include a wide variety of bioactive molecules that can enhance antioxidant activity, improve animal feed efficiency, stimulate digestive enzyme secretions, and boost the immunological responses against pathogens (Colmenero et al. 2003; Puvaça et al. 2016; Seidavi et al. 2021). These plant extract capabilities are mostly attributable to bioactive substances that exist in nature, such as thymol, flavonoids and glucosinolates isoprene derivatives (Garcia et al. 2007). Furthermore, the characteristics are most likely the primary mechanisms by which plants influence the production and health of birds (Rizzo et al. 2008). Meanwhile, they may exert their effects via increasing feed intake and endogenous secretions, as well as possessing antioxidant and antibacterial properties (Sakr et al. 2022). Using an appropriate solvent for extracting plant bioactive components is critical for preserving the chemical structure of desired bioactive compounds and increasing the efficiency of applied plant extract on bird production and health effect (Rossi et al. 2017). Ethanol is a safe extract solvent for plant extraction since it extracts non-toxic components and may yield safe oil products (Sultana et al. 2009). As a result, the FDA permit ethanol in food products. Besides, recent research has demonstrated that dietary supplementation with plant extracts may improve meat quality criteria in quail (Kaplan and Koksal 2021), and broiler (Bozkurt et al. 2012). Therefore, supplementing bird diets with such extracts may result in higher broiler production and meat quality features (Ener et al. 2011; Wang et al. 2015).

Paulownia trees have long been farmed in numerous countries, including China, Japan, Korea, the United States, and Bulgaria. These trees were firstly planted for their wood, which is used in the manufacturing of furniture, musical instruments, paper, flooring, and wall panels (Stewart et al. 2018). Paulownia is an economically significant multifunctional tree with a unique physicochemical characteristic that its leaves are suitable for food animal diet formulation as a fodder crop (Alagawany et al. 2020). Many efforts to incorporate paulownia leaves in animal feed have been documented, due to their high nutritional content (Al-Sagheer et al. 2019; Alagawany et al. 2020). For example, its leaves have been employed as fodder in many animal diets owing to their interesting and useful bioactive molecules content (Koleva et al. 2011). In addition, previous reports have proven that paulownia leaves are rich in minerals (including phosphorus, calcium, iron and zinc), as well as a high quantity of macro and microelements, crude protein, and essential amino acids (Zhu et al. 1986; Al-Sagheer et al. 2019). Moreover, paulownia leaves may also be collected and fed directly to goats and sheep (Mueller et al. 2001b).

Diet supplementation may be used to improve the efficiency of plant extracts by ensuring consistent mixing into formulated diets, uniform ingestion by birds, and avoiding waste (Dilawar et al. 2019). Also, previous studies showed that dietary supplementation with certain plant extracts might improve broiler performance, physiological response to stress and welfare of broilers (Alagawany et al. 2019; Yang et al. 2020). Therefore, it was important to demonstrate how the presence of such bioactive chemicals in paulownia leaves influences poultry performance and meat quality. Thus, the main purpose of the study was to investigate the effects of the PLE on carcase features, quality measurements, sensory attributes, and economic revenue of broiler meat.

**Materials and methods**

**Animal ethical statements**

All animal trials were carried out based on procedures and guidelines approved by the Animal Care Ethics of Animal Use in the Research Committee of Mansoura University (Code No: R/87).

** Preparation of paulownia (Paulownia tomentosa) leaf extract**

Fresh leaves of paulownia were harvested from a farm located near Bani Salama village, Wadi El-Natron, Behera governate, Egypt (N 30° 14’ E 26°). The leaves were washed under running water and dried at room
temperature to a consistent weight. The dried plant sample was crushed and sieved to a particle size of 105 mm on average. Next, the sample was kept in a dark, airtight polyethylene bag in a 4 °C refrigerator until the extraction process began. The extraction method followed the Sutthi et al. (2020) procedure with a small modification. Briefly, the crushed leaves were weighed and blended with a 70% ethanol solution (Sigma-Aldrich (M) Sdn Bhd, Selangor, Malaysia) in the ratio of 1:2 (w/v) in 1 L dark flasks. At room temperature, the prepared mixture was shaken at 100 rpm x g for 24 h using an automatic shaker. The obtained mixture was filtered using a sterile muslin cloth. The obtained solvent was then evaporated using a rotary evaporator (Rotavapor Model R-144 with Water Bath Model B-481; Buchi, Switzerland) at 65 °C and then determined the dry weight using a freeze-drying method as described by Harikrishnan et al. (2009). The leaf powder was stored at −20 °C until use.

**Gas chromatography/mass spectrometry**

Gas Chromatography/Mass Spectrometry (GC-MS) analysis of the ethanol extract of paulownia leaves was performed using a PerkinElmer GC Clarus 500 system (PerkinElmer Instruments, Waltham, MA) comprising an AOC-20i auto-sampler and a gas chromatograph interfaced to a mass spectrometer (GC-MS) equipped with an Elite-5MS (5% diphenyl/95% dimethyl poly siloxane) fused a capillary column (30 μm x 0.25 μm ID x 0.25 μm df). The GC-MS analysis was performed according to Ezhilan and Neelamegam (2012) procedure. The GC-MS detection depends on an electron ionisation system via electron impact mode with ionisation energy of 70 eV and carrier gas (Helium gas, 99.999%) at a constant flow rate of 1 mL/min, and an injection volume of 2 μL was employed (a split ratio of 10:1). The injector temperature was maintained at 250 °C, the ion-source temperature was 200 °C, the oven temperature was programmed from 110 °C (isothermal for 2 min), with an increase of 10 °C per min to 200 °C, then 5 °C/min to 280 °C, ending with a 9-min isothermal at 280 °C. Mass spectra were taken at 70 eV, a scanning interval of 0.5 s and fragments from 45 to 450 Da. The solvent delay was 0 to 2 min, and the total GC/MS running time was 36 min. Data from bioactive detectable compounds in PLE are reported in Table 1 and the chromatograms are shown in Figure 1. The presence of specific bioactive compounds in PLE extract was identified by comparing the chromatographic peaks with the retention time ($R_t$) of individual standards and further confirmed by co-injection with isolated standards. The amount of specific bioactive compounds present in the extract is expressed as mg/g. The mass-detector used in this analysis was Turbo-Mass Gold-PerkinElmer, and Turbo-Mass v-5.2 software was adopted to handle mass spectra and chromatograms. Interpretation of GC-MS spectra was conducted using the database of the National Institute Standard and Technology (NIST) having more than 62,000 patterns. The spectrum of the unknown components was compared with the spectrum of known components stored in the NIST library. The names, molecular weights, and structures of the components of the test materials were ascertained.

**Animals and diets**

A total of one-hundred eighty-one-day-old male Cobb chicks were randomly allotted to four dietary treatments containing four levels of paulownia extract (0, 0.1, 0.3 and 0.5 g kg$^{-1}$). The PLE tested levels were chosen based on the results of Farahat et al. (2021). The chicks were allocated into equal four groups (5 replicates with 9 birds each). All birds were housed in an open-sided house with a rice hull litter floor with 20 pens. Feed and water were supplied for ad-libitum. Over the first 7 days, the birds were exposed to light for 24 h a day and then the photoperiod was gradually reduced (2 hr a week) until reached 20 h per day at age 3 weeks old and then lasted to the end of the experiment. The initial temperature of 33 °C was gradually lowered to 26 °C until day 21 and then maintained constant after that point. The health of chicks was carefully examined, and the mortality rate was recorded daily. The feeding program was divided into two phases: starter (0–21 d) and grower (22–42 d). To fulfill the nutritional requirements of the birds, formulated pelleted diets based on maize and soybeans were offered to them (Vantress 2015) (Table 2). Diets were pelleted using a steam pellet mill (Koppers Junior C40, Koppers Company, Inc., Pittsburgh, PA, USA) with a 37 kW Siemens motor. Whereas, the conditioning time was approximately 10 s at 75 °C and under a pressure of 1.5 kg per cm$^2$. The prepared

| Bioactive compound   | Retention time | Peak area % | Amount (mg/g) |
|----------------------|----------------|-------------|---------------|
| Thymol               | 7.86           | 82.37       | 8.94          |
| α-Tocospiro          | 26.59          | 3.18        | 3.72          |
| Phyto1               | 19.04          | 9.28        | 0.97          |
| Pentadecanoic acid   | 16.82          | 2.39        | 0.27          |
| Octasiloxane         | 36.59          | 2.78        | 0.19          |

$\text{Bioactive compound Retention time Peak area % Amount (mg/g)}$
Pelleted diets were 4.7 mm in diameter and 50 mm in thickness.

Slaughter and carcase measurements

Five birds from each pen were randomly selected for carcase and meat quality characteristics measurements on day 42 of the trial. After 10 hours of deprivation of food and drink, a sharp knife was used to cut the jugular vein to ensure maximum and quick blood loss for humane slaughter. Shanks, intestines as well as abdominal fat were removed. Carcase and giblets weights were recorded. Carcase yield was calculated by the difference of live weight and dressed weight and expressed in percentage. Breast and thigh meat were separated and weighted individually.

Sensory evaluation

Twenty pieces of chicken halves were selected from each group and subjected to a 60-min heat treatment at 200°C. Parts of the thigh and breast were sensory examined independently from each half. A semi-trained panel of six co-workers belonging to meat Mansoura university laboratory assessed heat-treated

Table 2. Diet formulation and chemical analysis.

| Ingredients                      | Starter diet (%) | Grower diet (%) |
|----------------------------------|------------------|-----------------|
| Maize                            | 52.3             | 54.5            |
| Corn gluten meal 30%             | 2.5              | 0               |
| Corn gluten meal 60%             | 2.5              | 1.6             |
| Canola meal                      | 15               | 14              |
| Poultry by product meal<sup>a</sup> | 4                | 6               |
| Soybean meal (Hi-Pro)            | 19               | 17.8            |
| Poultry oil<sup>b</sup>          | 2                | 3.8             |
| Limestone                        | 1                | 0.9             |
| Salt                             | 0.1              | 0.1             |
| Di-calcium phosphate             | 0.4              | 0.25            |
| Sodium-bi-carbonate              | 0.18             | 0.2             |
| Lysine Sulphate 70%              | 0.43             | 0.32            |
| DL-Methionine 99%                | 0.19             | 0.19            |
| L-Threonine                      | 0.08             | 0.02            |
| Premix<sup>c</sup>               | 0.32             | 0.32            |
| Total                            | 100              | 100             |

**Chemical composition**

| Crude protein (%) | ME<sup>d</sup> (Kcal/Kg) | Dig. Lysine<sup>e</sup> (%) |
|-------------------|---------------------------|----------------------------|
| 23                | 2900                      | 1.27                       |
| 22                | 3050                      | 1.19                       |

<sup>a</sup>Poultry by-product meal, pet food grade, Griffin Industries Inc., Bastrop, Texas, 66.3% crude protein (CP).

<sup>b</sup>Poultry oil, Berg and Schmidt India, Hamburg, Germany, 99% crude fat, 8700 Kcal metabolic energy.

<sup>c</sup>each 1 kg of mineral premix and vitamin contain; Choline Chloride 70%, Dicalcium 98%, Dilazuril 1%, Kemzyme, Vitamin A 20000000 I.U, Vit-D3 6000000 I.U, Vit-E 60000 mg, Vit-K3 4000 mg, Vit-B1 4000 mg, Vit-B2 12000 mg, Vit-B6 8000 mg, Vit-B12 20000 mcg, Nicotinamide 80000 mcg, Biotine 20000 mcg, Folic acid 2000 mcg, Ca d-pantothenate 20000 mcg, Manganese 150000 mcg, Zinc 120000 mg, Iron 96000 mcg, Copper 20000 mg, Iodine 20000 mg, Selenium 400 mg.

<sup>d</sup>ME, calculated Metabolisable Energy.

<sup>e</sup>Dig. Lysine, Digestible Lysine.

Figure 1. GC-mass chromatogram of paulownia leaf extract (PLE) (**above**) and standard main bioactive compounds (**below**).
broiler samples. A semi-trained panel evaluated the sensory qualities of fresh meat and meat products from the different treated groups. Training consisted of a 30-min training session on identifying hedonic meat quality qualities. Using a 10-point category scale, the meat samples used for sensory assessment tests were divided into groups based on the category scaling approach, which evaluated juiciness, tenderness, flavour intensity, and overall acceptability. Each panelist was informed about the meat preparation and graded attributes prior to each session. The panellists were not told the meat source (treated groups). A supply of water and crackers was on hand to flush off any lingering odours from prior samples. During the sensory evaluation sessions, panellists were not allowed to communicate with each other. The pH was directly measured with a pH metre (testo 205, Rausser, Ebmatingen, Switzerland) in the right breast and leg muscles.

**Meat quality and composition**

The drip loss and boiling loss using the procedures described by Zhou et al. (2010) and were calculated using the following formula:

\[
\text{Drip loss (\%)} = \left(\frac{\text{initial weight} - \text{final weight}}{\text{initial weight}}\right) \times 100\%;
\]

\[
\text{Boiling loss (\%)} = \left(\frac{\text{raw weight} - \text{cooked weight}}{\text{raw weight}}\right) \times 100\%.
\]

Shear force was determined using a texture analyser (C-LM3B, Tenovo International Co., Ltd., Beijing, China) and was expressed in N and was measured perpendicular to the axis of muscle fibre in 5 replicates for each treatment.

Water holding capacity was determined in the pectoralis major muscle following the filter press procedure as described by Pekel et al. (2020). Briefly, approximately 5 g of minced meat sample was divided into 5 parts and put between two filter sheets (15 × 15 cm) that were weighed and then placed under 2,250 g of weight pressure for 5 min. After removing the sample from the filter papers, the filter papers were weighed again, and the displaced water was expressed as a percentage of the original weight of meat flesh added between the two filter sheets.

**Nutrient composition of breast and thigh meat**

Using an ultra-centrifugal rotor mill grinder (Retsch ZM 200; Retsch GmbH Co, KG, Haan, Germany), specimens were crushed into pieces able to pass through a 0.5 mm screen. All estimated nutrients were verified in triplicate. The dry matter contents were estimated via drying samples in an oven (Memmert 500; Memmert GmbH, Schwabach, Germany) at 105 °C for 18 h (method 930.15; AOAC (2006)). The ash content was assessed through the Ashing process using a muffle furnace overnight at 600 °C (method 942.05; AOAC (2006)). The gravimetric extraction procedure was applied to estimate the ether extract content using a Soxhlet apparatus (Model Soxtherm 416; Gerhardt Laboratory Systems GmbH, Koenigswinter, Germany) with a petroleum benzene solution for nearly 2 h and 15 min (method 920.39; AOAC (2006)). After samples were treated with sulphuric acid in a digestor (Gerhardt Kjeldatherm KB, Bonn, Germany), samples’ nitrogen contents were estimated using the Kjeldahl procedure via a Kjeltec analyser (method 984.13; AOAC (2006)). The obtaining ammonium sulphate was refined by NaOH in a distillation unit (Gerhardt Vapodest 50 Carrousel, Germany). Then, crude protein concentrations were calculated by multiplying the calculated nitrogen values by a constant factor (6.25). Wet digestion with nitric-perchloric acid was used to prepare samples for total protein determination. The creation of a phospho-molybdenum complex was applied to quantify the level of protein using acid molybdate and Fiske-Subbarow reducer solutions. The protein quantities in the digested samples were then measured using a spectrophotometer (Biotek Synergy Neo2; Biotek Instruments, Winooski, VT) with the absorbance at 620 nm (method 946.06; AOAC (2006)).

**Collagen content**

Five equal specimens per each group were frozen in liquid nitrogen at −176 °C and crushed into powder for the assessment of soluble and insoluble collagen content according to the Hill (1966) technique with minor modifications. Quadruplicate 3 g meat specimens were mixed with 16 mL of 1/4 strength Ringer’s solution, heated at 77 °C for 70 min in a hot water bath, then centrifuged at room temperature at 3,600 rpm for 10 min, and filtered using Whatman ashless 09-795 paper (Whatman Ltd., Maidstone, England). For each sample, 2 aliquot parts were used to estimate soluble collagen: remains were blended with 8 mL of 1/4 strength Ringer’s solution, then centrifuged under the same previously mentioned conditions, and
mixed with 25 mL of concentrated HCl. The meat residues were blended with 25 mL of 6 N HCl for estimated the insoluble collagen. Both soluble and insoluble specimens prepared solutions were preserved within autoclave at 121°C, 18–20 psi, for 18 h, their pH was corrected to 6.00, then the obtained specimens were diluted to 250 and 500 mL, and they were filtered using a Whatman 09-795 filter paper.

Spectrophotometric estimation of collagen was applied as ascribed by Bergman and Loxley (1963) procedure. Consequently, 2 mL of isopropanol, 1 mL of an oxidant solution (7% w/v chloramine T, 1 volume, and acetate/citrate buffer, pH 6.0, 3 volumes), and 4 mL of Ehrlich's reagent were added to each sample using a pipette. Tubes were preserved within the incubator at 60°C for 25 min and cooled. Spectrophotometric estimation of the hydroxyproline level was applied at 558 nm via a Jasco V-630 spectrophotometer (Jasco, Easton, MD); the following equations were applied to convert g of hydroxyproline/mL of the solution to mg of collagen/g of meat:

Collagen per gram of meat (mg) = [(μg/mL) × dilution factor × constant]/sample wt × 1000

With 250 and 500 applied as dilution factors and 7.52 and 7.25 presented as constants for soluble and insoluble collagen, respectively. Total soluble was presented as the sum of the soluble and insoluble collagen concentrations.

**Economic efficiency**

The parameters of economic efficiency involved in this study were productive cost, return and net profit. The cost parameters include total variable cost (TVC), total fixed cost (TFC) and the total cost (TC) calculated as the sum of both TVC and TFC. The TVC includes the broilers of purchased price and feed costs (feed ingredients and paulownia) for each experimental group. While the TFC includes laboratory costs, veterinary care costs (vaccines, drugs and veterinary supervision), litter, water, electricity, and miscellaneous costs plus rent value were calculated according to Ani and Ugwuowo (2011). The total return (TR) was calculated as the sum of sales of final body weights and litter (Hassan et al. 2016). The net profit (NP) was measured according to Kamel and Mohamed (2016) as the difference between TR and TC.

**Statistical analysis**

The calculated and measured data were statistically examined using one-way ANOVA via SPSS software (IBM SPSS Ver. 22, IMB Corp., Armonk, NY). All acquired data were checked for normality and homogeneity. Tukey’s range test was applied to assess the significant differences between means at a confidence level of 95% (P < 0.05). Orthogonal polynomial contrasts are applied to assess significant trends (linear or quadratic). The collected results were illustrated in tables as Mean ± SEM.

**Results**

**Carcass traits**

The effects of dietary supplementation with different levels of PLE on carcass characteristics of broiler chickens are shown in Table 3. The chicken group fed diets supplemented with PLE (linear; P < 0.001) significantly increased live weight, carcass weight, breast weight, and thigh weight compared to the control group. However, there were no significant (linear; P > 0.05) differences in carcass yield among the different groups. Additionally, birds fed on a high level of PLE-supplemented diets had higher (linear; P < 0.05) weights for liver, heart, and gizzard than those of birds fed the control diet.

**Table 3.** The effects of paulownia leaf extract (PLE) supplemented diets at different levels (0.0, 0.1, 0.3 and 0.5 g kg⁻¹) on broiler carcass characteristics (n = 5).

| Parameters            | CNT       | PLE0.1    | PLE0.3    | PLE0.5    | SEM    | P value       |
|-----------------------|-----------|-----------|-----------|-----------|--------|---------------|
| Live weight (g)       | 2.08      | 2.23      | 2.15      | 2.21      | 0.25   | <0.001        |
| Carcase weight (g)    | 1.23      | 1.20      | 1.20      | 1.21      | 0.12   | <0.001        |
| Carcase yield %       | 68.3      | 68.3      | 68.3      | 68.3      | 0.3    | 0.12          |
| Breast weight (g)     | 0.95      | 0.95      | 0.95      | 0.95      | 0.05   | <0.001        |
| Thigh weight (g)      | 0.45      | 0.45      | 0.45      | 0.45      | 0.05   | <0.001        |
| Liver weight (g)      | 0.10      | 0.10      | 0.10      | 0.10      | 0.01   | <0.001        |
| Heart weight (g)      | 0.02      | 0.02      | 0.02      | 0.02      | 0.01   | <0.001        |
| Gizzard weight (g)    | 0.05      | 0.05      | 0.05      | 0.05      | 0.01   | <0.001        |

PLE, paulownia leaf extract; CNT, control group fed un-supplemented diet.
a,b and c the same superscript letters within the same row indicate no significance differences, while different letters indicate significant differences (P < 0.05).
Meat quality indices and proximate analysis

Enriched broiler chicken diets with different levels of PLE significantly ($P < 0.001$) affected the meat composition (Table 4). Birds fed PLE-supplemented diets had lower collagen content in breast muscle compared to the control group with the highest level in those that received 0.1 g/kg of diet. Although the collagen content of thigh muscle was significantly (Quadratic; $P < 0.001$) lower in groups fed with PLE at levels of 0.3 and 0.5 g/kg of diet, whereas the highest value was recorded in the group fed the PLE supplemented diet at the level of 0.1 g/kg followed by the control group. In comparison to the control group, a fed broiler diet supplemented with graded amounts of PLE demonstrated a remarkable (Quadratic; $P < 0.001$) decrease in total lipids in breast muscle. The lowest value of the total lipids in breast muscle was found in birds that received the 0.5 g/kg PLE supplemented diet. Birds fed PLE-supplemented diets at levels of 0.3 and 0.5 g/kg had a significantly decreased levels of the total lipids in thigh muscles compared to the control group. Dietary supplementation with showed significant (linear; $P < 0.001$) differences in the values of protein content in breast and thigh muscles. The highest value of protein content in breast muscle was observed in birds fed with 0.5 g PLE, while birds fed with 0.1 g/kg PLE had the highest protein content in thigh muscle compared to other groups.

Sensory attributes indices and pH24

The effect of dietary supplementation with different levels of PLE on sensory evaluation and pH24 of broiler chicken meats are presented in Table 5. Subjective evaluation of the breast meat did not show significant differences among treatments from the different groups for tenderness and acceptability. However, flavour and juiciness significantly (linear; $P < 0.001$) increased in birds fed with PLE-supplemented diets in a dose-dependent manner. The results of subjective evaluation of the thigh meat showed significant improvement in meat quality (flavour, tenderness, juiciness, and overall acceptability) for groups fed on PLE-supplemented diets. The evaluation score of sensory attributes for flavour, tenderness, and juiciness significantly increased with increasing the levels of PLE in broiler diets. However, there were no significant differences between the control group and PLE 0.1 and 0.3 groups for juiciness. The results showed that the highest score of the overall acceptability for thigh meat of birds fed on a diet supplemented with PLE was at the level of 0.3 g/kg. Dietary supplementation with the different levels of PLE did not show significant effects on the pH24 values of breast and thigh meat (Table 5).

Economic analysis

The effects of dietary supplementation with different levels of PLE on economic measures and total costs are presented in Table 6. The results showed a significant decrease (Quadratic; $P < 0.001$) in the production costs of broiler chicken meat when PLE was added to the feeds. The lowest production costs were observed in birds fed with 0.1 g/kg PLE followed by the control group. The highest production costs were observed in birds fed with 0.5 g/kg PLE. Dietary supplementation with PLE significantly decreased (Quadratic; $P < 0.001$) the feed conversion ratio (FCR) in broiler chicken. The lowest FCR was observed in birds fed with 0.3 g/kg PLE, while the highest FCR was recorded in birds fed with 0.5 g/kg PLE. The results showed that the addition of PLE to the feeds significantly decreased (Quadratic; $P < 0.001$) the feed costs in broiler chicken. The lowest feed costs were observed in birds fed with 0.1 g/kg PLE followed by the control group. The highest feed costs were observed in birds fed with 0.5 g/kg PLE. Dietary supplementation with PLE significantly decreased (Quadratic; $P < 0.001$) the mortality rate in broiler chicken. The lowest mortality rate was observed in birds fed with 0.1 g/kg PLE, while the highest mortality rate was recorded in birds fed with 0.5 g/kg PLE. The results showed that the addition of PLE to the feeds significantly decreased (Quadratic; $P < 0.001$) the overall costs in broiler chicken. The lowest overall costs were observed in birds fed with 0.1 g/kg PLE followed by the control group. The highest overall costs were observed in birds fed with 0.5 g/kg PLE.

Table 4. The effects of paulownia leaf extract (PLE) supplemented diets at different levels (0.0, 0.1, 0.3 and 0.5 g kg$^{-1}$) on broiler breast and thigh meat quality indices ($n = 5$) and proximate composition ($n = 3$).

| Parameters                  | CNT | PLE0.1 | PLE0.3 | PLE0.5 | SEM | Combined | Linear | Quadratic |
|-----------------------------|-----|--------|--------|--------|-----|----------|--------|-----------|
| **Breast measurements**     |     |        |        |        |     |          |        |           |
| Total collagen, mg/g        | 4.92 | 4.66a  | 4.42b  | 4.21b  | 1.12| 0.002    | 0.001  | 0.066     |
| Soluble collagen, mg/g      | 1.21 | 1.05ab | 1.12b  | 0.79c  | 0.87| <0.001   | 0.021  | <0.001    |
| Total lipids, %             | 1.37 | 1.24b  | 1.20b  | 1.11c  | 0.92| <0.001   | 0.064  | <0.001    |
| Total protein, %            | 24.38 | 25.03b | 25.16b | 25.94a | 1.04| <0.001   | <0.001 | 0.093     |
| Drip loss, %                | 2.63 | 3.01   | 3.11   | 2.91   | 2.31| 0.091    | 0.083  | 0.274     |
| Boiling loss, %             | 22.12 | 22.02  | 21.94  | 22.23  | 0.69| 0.541    | 0.591  | 0.328     |
| Moisture %                  | 74.71 | 74.51  | 74.68  | 74.73  | 1.26| 0.412    | 0.351  | 0.062     |
| Crude ash %                 | 0.84 | 0.81   | 0.77   | 0.83   | 1.02| 0.145    | 0.057  | 0.071     |
| **Hip measurements**        |     |        |        |        |     |          |        |           |
| Total collagen, mg/g        | 6.35 | 5.89a  | 5.24b  | 4.73b  | 2.03| 0.051    | 0.120  | 0.048     |
| Soluble collagen, mg/g      | 2.65 | 2.32b  | 1.56b  | 1.02c  | 1.68| 0.004    | 0.002  | 0.037     |
| Total lipids, %             | 3.71 | 2.09b  | 1.47b  | 1.38c  | 0.97| <0.001   | 0.084  | <0.001    |
| Total protein, %            | 19.41 | 20.96b | 22.63b | 22.96c | 1.08| <0.001   | <0.001 | 0.761     |
| Drip loss, %                | 2.55 | 2.75   | 3.14   | 3.07   | 1.53| 0.345    | 0.214  | 0.305     |
| Boiling loss, %             | 19.62 | 19.22  | 19.81  | 19.19  | 0.73| 0.081    | 0.067  | 0.125     |
| Shear force, N              | 8.75 | 8.88   | 9.01   | 9.11   | 1.55| 0.062    | 0.059  | 0.241     |
| Moisture %                  | 74.69 | 74.72  | 74.85  | 74.96  | 1.46| 0.324    | 0.165  | 0.265     |
| Crude ash %                 | 0.82 | 0.84   | 0.79   | 0.78   | 1.35| 0.252    | 0.312  | 0.095     |

PLE, paulownia leaf extract; CNT, control group fed un-supplemented diet. a,b and c the same superscript letters within the same row indicate no significance differences, while different letters indicate significant differences ($P < 0.05$).
Production revenue of broiler chickens are given in Table 6. The economic return analysis did not show significant ($P > 0.05$) differences in cost parameters. However, the economic efficiency indicators such as body weight sales, total returns, and net profit were improved in all groups treated with PLE compared to the control group. The highest (linear; $P > 0.05$) values of body weight sales, total returns, and net profit were observed in the group that received the PLE supplemented diet at the level of 0.5 g/kg, followed by the group that received 0.1 g/kg, and then the group received 0.3 g/kg; although values for 0.1 g/kg and 0.3 g/kg were not significantly different ($P > 0.05$).

Table 5. The effects of paulownia leaf extract (PLE) supplemented diets at different levels (0.0, 0.1, 0.3 and 0.5 g kg$^{-1}$) on broiler sensory attributes indices and pH$_{24}$ ($n = 20$).

| Parameters       | CNT | PLE$_{0.1}$ | PLE$_{0.3}$ | PLE$_{0.5}$ | SEM | Combined  | Linear     | Quadratic  |
|------------------|-----|-------------|-------------|-------------|-----|-----------|------------|------------|
| Breast muscle    | 9.24$^d$ | 9.36$^c$ | 9.54$^b$ | 9.62$^a$ | 1.32 | $<0.001$ | $<0.001$ | 0.347      |
| Flavour          | 8.91 | 8.99 | 8.87 | 8.92 | 0.64 | 0.469 | 0.526 | 0.562      |
| Tenderness       | 8.93$^c$ | 9.14$^{bc}$ | 9.22$^{ab}$ | 9.37$^a$ | 1.64 | $<0.001$ | $<0.001$ | 0.908      |
| Juiciness        | 8.73 | 8.82 | 8.88 | 8.90 | 1.01 | 0.112 | 0.097 | 0.326      |
| Acceptability    | 5.87 | 5.89 | 5.91 | 5.92 | 0.97 | 0.398 | 0.529 | 0.493      |
| pH$_{24}$        | 5.99 | 6.03 | 6.05 | 6.06 | 1.42 | 0.035 | 0.037 | 0.182      |

PLE: paulownia leaf extract; CNT, control group fed un-supplemented diet.
a,b and c the same superscript letters within the same row indicate no significance differences, while different letters indicate significant differences ($P < 0.05$).

Table 6. The effects of paulownia leaf extract (PLE) supplemented diets at different levels (0.0, 0.1, 0.3 and 0.5 g kg$^{-1}$) on economic return and total production revenue.

| Parameters       | CNT | PLE$_{0.1}$ | PLE$_{0.3}$ | PLE$_{0.5}$ | SEM | Combined  | Linear     | Quadratic  |
|------------------|-----|-------------|-------------|-------------|-----|-----------|------------|------------|
| Total chicks’ cost | 30 | 30 | 30 | 30 | 0.23 | 0.992 | 0.968 | 1.263      |
| PLE cost         | 0.00 | 0.02 | 0.04 | 0.1 | 0.01 | 0.462 | 0.502 | 0.395      |
| TFI cost         | 136.45 | 144.68 | 145.65 | 143.04 | 1.09 | 0.398 | 0.502 | 0.395      |
| TVC              | 166.45 | 174.68 | 175.65 | 173.04 | 1.19 | 0.153 | 0.221 | 0.179      |
| Litter cost      | 5.99 | 6.03 | 6.05 | 6.06 | 1.42 | 0.035 | 0.037 | 0.182      |
| Labor cost       | 16.67 | 16.67 | 16.67 | 16.67 | 0.53 | 0.785 | 0.371 | 0.651      |
| W& Elec. cost    | 37.5 | 37.5 | 37.5 | 37.5 | 0.13 | 0.057 | 0.112 | 0.051      |
| VM costs         | 4.17 | 4.17 | 4.17 | 4.17 | 0.45 | 0.268 | 0.957 | 0.241      |
| TFC              | 95.82 | 95.82 | 95.82 | 95.82 | 1.11 | 0.598 | 0.524 | 0.106      |
| TC               | 262.26 | 270.5 | 271.47 | 268.86 | 1.9 | 0.375 | 0.329 | 0.119      |
| BW sales         | 276.25$^c$ | 350.90$^b$ | 343.20$^b$ | 408.85$^a$ | 5.41 | $<0.001$ | $<0.001$ | 0.345      |
| Litter sales     | 3.33 | 3.33 | 3.33 | 3.33 | 3.06 | 0.297 | 0.301 | 0.412      |
| TR               | 17.32$^c$ | 83.73$^b$ | 75.06$^b$ | 143.32$^a$ | 4.91 | 0.002 | 0.003 | 0.051      |
| NP               | 12.5 | 12.5 | 12.5 | 12.5 | 1.03 | 1.012 | 0.751 | 0.967      |
| $L.E$: Egyptian Pound. *Price of kg broiler sale at the time of experiment = 30 L.E.*
PLE: paulownia leaf extract; CNT: control group fed un-supplemented diet; SEM: Standard Error of Mean; W& Elec.: water and electricity cost; VM cost: veterinary and management cost; BW sales: body weight sales; TC: Total costs; TFI: total feed intake; TVC: Total variable costs, TFC: Total fixed costs, TR: Total returns, NP: Net profit.
a,b and c the same superscript letters within the same row indicate no significance differences, while different letters indicate significant differences ($P < 0.05$).

Discussion

In the current study, the final live body, carcase, breast, thigh, liver, heart, and gizzard weight increased significantly in all broiler groups fed PLE-supplemented diets. The broiler group administered diets enriched with the highest level of PLE at 0.5 g/kg had a high final biomass production, and carcase, thigh, heart, and gizzard weights. These results were found to be in line with Alcicek et al. (2004) that showed final live weight, carcase weight, and weight after defeating increased with rising levels of Moringa (Moringa oleifera) leaf and fruit powders in broiler diets. Moreover, Ahmadian et al. (2020) demonstrated that supplementing male Ross broiler chicks with...
2% thyme significantly improved carcase and kidney weight in comparison with other experimental groups. Many studies have been published on the use of essential oils in chicken diets, which enhanced growth, improved carcase quality, and increased survival rates (Williams 2001). These features of plant components as food animal dietary supplements may be related to the function of PLE bioactive compounds, particularly thymol, which accounted for 82.37% of total bioactive molecules found in PLE (Table 1). Thymol, a key component of these extracts, is mainly responsible for these actions (Yanishlieva et al. 1999).

Several studies have shown that the nutritional quality of proteins in chicken fillets may be diminished due to low collagen digestibility and a lack of some essential amino acids (e.g. tryptophan, sulphur amino acids, and lysine) found in connective tissue in relation to myofibrillar and sarcoplasmic proteins exist (Boback et al. 2007; Petracci et al. 2014; Chen et al. 2016). Thus, chicken breast has low fat and collagen concentrations, the latter of which is better for digestion and consumer health (Thanatsang et al. 2020). With regard to our breast and thigh meat analyses, it was shown that the broiler chickens fed higher inclusion levels of PLE in their consumed meals had lower collagen and lipids content as well as higher total protein content. These results found in similar to those of Popović et al. (2019) who reported that a dietary essential oils mixture of thyme (Thymus vulgaris), oregano (Origanum vulgare) and rosemary (Rosmarinus officinalis) significantly improved poultry meat contains from protein while reducing collagen and fat concentrations, so that can be considered as dietetic food. Also, curcumin-supplemented diets with or without thymol, significantly enhanced meat quality in broilers through the lowering of total saturated fatty acid levels while considerably increasing monounsaturated/polyunsaturated fatty acid levels in broilers (Galli et al. 2020). Furthermore, Luna et al. (2010) indicated that the dietary inclusion of thymol or carvacrol might be useful to enhance poultry meat quality. The strong antioxidant properties of thymol (Abd El-Naby et al. 2020), which have comparable efficiency in retarding lipid oxidation (Luna et al. 2010), may be responsible for the improvement in the quality of broiler meat.

Acceptability, juiciness, tenderness, and flavour of poultry meat are the most essential and detectable meat characteristics that affect customers’ evaluation before purchasing any type of meat product (Mir et al. 2017a). Furthermore, measurable qualities, such as pH24, are critical for the production of value-added meat products (Batool et al. 2021). The nutrition of birds has a considerable influence on the quality and safety of the meat (Seidavi et al. 2021). Our research sensory characteristics indicators revealed that increasing the PLE inclusion level in the broiler diet enhanced breast muscle taste and juiciness as well as thigh muscle flavour, tenderness, juiciness, and acceptability. These findings are consistent with those of Purwanti et al. (2019) and Camy et al. (2020) demonstrating that dietary supplementation of several herbal plants or their leaf extracts improved the sensory and physical properties of broiler meat. The improvement in sensory and physical meat qualities may be attributed to the strong antioxidant activity of PLE bioactive molecules, which decreased meat oxidation that began immediately after slaughter and may prevent this oxidation from negatively altering the colour and taste of meat (Aberle et al. 2001; Abdelatty et al. 2020).

Assessing all cost elements and how they vary across integrated broiler production systems is complicated (Basurco et al. 2015) and beyond the scope of this study. According to the findings of our basic economic study, the body weight sales, net profit, and total return were considerably higher in the experimental group than in the control group. Furthermore, these results demonstrated that including paulownia leaf extract in broiler diets at a level of up to 0.5 g was the most economically beneficial. The results of the current study were found to be in line with those of Yitbarek (2012); Kamel et al. (2016); Abd El-Aziz et al. (2020) and Shehata et al. (2018) demonstrating that alternate feed resources may increase farm profitability by increasing growth, improving feed efficiency, and lowering diet costs.

### Conclusion

In conclusion, the results of this study indicate that a PLE diet can elicit increases in live weight, carcase weight, breast weight, and thigh weight while promoting reductions in collagen and lipid contents in the breast and thigh muscles of broiler chickens. Moreover, PLE-supplemented chicks exhibited better results with respect to improvement in meat quality (flavour, tenderness, juiciness, and overall acceptability) compared to control chickens. Furthermore, the economic efficiency indicators such as body weight sales, total returns, and net profit were improved in all groups treated with PLE compared to the control group. Thus, supplementing broiler diets with 0.5 g/kg PLE could improve body weight, carcass features, meat quality, sensory attributes, and economic efficiency. Also, further studies on the impact of
PLE-enriched broiler diets in producing meat that is safe for customers and of high quality should be recommended.

Disclosure statement
All of the authors state that they have no conflicts of interest.

Author contributions
Shimaa A. Sakr, Mona M. Elghareeb and Huda A. EL-Emam, involved in data curation, formal analysis, funding acquisition, investigation, methodology, resources, software, and writing—original draft. Mohammed A. E. Naiel, Noha M. Wahed and Hanan A. Zaher, involved in conceptualisation, data curation, funding acquisition, investigation, methodology, project administration, resources, supervision, validation, visualisation, writing—original draft, and writing—review and editing. Mohamed Mohamed Soliman, Mustafa Shukry, Adil Alkhedaide and Abdelrazeq M. Shehata, involved in conceptualisation, data curation, formal analysis, funding acquisition, investigation, methodology, project administration, resources, software, supervision, validation, visualisation, writing—original draft, and writing—review and editing.

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ORCID
Mohammed A. E. Naiel http://orcid.org/0000-0002-8172-5366

Data availability statement
The datasets presented and/or applied during the current study are available from the corresponding author on reasonable request.

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