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# Bio-preservation effect of lactic acid bacteria postbiotics on physical, chemical, and sensory properties of vacuum-packaged broiler breast meat

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ABSTRACT

Increasing consumer demand for quality broiler meat has driven interest in natural preservatives, particularly postbiotics of lactic acid bacteria (LAB). This study explored the use of concentrated cell-free supernatants (CFS) from *Lactobacillus acidophilus* (LA) and *Lacticaseibacillus rhamnosus* GG (LGG) as marinades to improve the physicochemical and sensory attributes of vacuum-packaged broiler breast meat. Meat samples (35 g) were marinated with CFS (500 µL/mL; 5:1 ratio), vacuum-sealed, and stored at 4°C for 10 days. Evaluations were conducted on days 0, 3, 7, and 10. Key indicators, including pH, water-holding capacity (WHC), drip loss (DL), cooking loss (CL), lipid oxidation (TBARS), color, and texture, were analyzed using standard techniques (TBARS assay, colorimetry, texture profile analysis). Sensory panels evaluated the color, texture, odor, and acceptability. Both postbiotics significantly enhanced meat quality by lowering pH (6.03-6.04), TBARS value (0.694-0.678 mg MDA/kg), and DL (2.38-2.46 %), while increasing WHC (73.09-71.01 %) than the control (6.28, 0.829 mg MDA/kg, 3.02 %, and 59.94 %, respectively). Postbiotics preserved color, with higher $a^*$ (3.12-3.74 vs 1.68) and $b^*$ (16.32-16.95 vs 13.87) values, with improved texture of both raw and cooked meat. LGG postbiotics showed superior antioxidative effects, while LA postbiotics improved sensory attributes (color score: 4.00 vs 2.33 in control). The practical application of LA and LGG postbiotics as natural bio-preservatives in meat processing, offering clean-label solutions for prolonging shelf life and quality enhancement in broiler meat. Although the specific metabolites were not identified, these findings mark a novel, targeted approach to postbiotics use in meat preservation.

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*Abbreviations*

| | |
|---|---|
| ATCC | American Type Culture Collection |
| ATP | Adenosine triphosphate |
| ANOVA | Analysis of variance |
| AU | Arbitrary Unit |
| BCSIR | Bangladesh Council of Scientific and Industrial Research |
| BLRI | Bangladesh Livestock Research Institute |
| BLIS | Bacteriocin-Like Inhibitory Substances |
| CL | Cooking loss |
| CFS | Cell-free supernatant |
| CFU | Colony-forming unit |
| DMRT | Duncan's Multiple Range Test |
| DP | Drip loss |
| EPS | Exopolysaccharides |
| EU | European Union |
| GRAS | Generally Recognized as Safe |
| GLM | General linear model |
| HCl | Hydrochloric acid |
| LAB | Lactic acid bacteria |
| LA | *Lactobacillus acidophilus* |
| LGG | *Lacticaseibacillus rhamnosus* |
| LB | Luria Bertani |
| MDA | Malondialdehyde |
| MRS | De Man Rogosa Sharpe agar |
| NBRC | National Institute of Technology and Evaluation, Biological Resource Centre |
| NITE | National Institute of Technology and Evaluation |
| OD | Optical density |
| PBS | Phosphate Buffered Saline |
| SEM | Standard Error of Mean |
| SD | Standard Deviation |
| SPSS | Statistical Package for the Social Sciences |
| TBARS | Thiobarbituric acid reactive substances |
| UPM | Universiti Putra Malaysia |
| UiTM | Universiti Teknologi MARA |
| USA | United States of America |
| WHC | Water holding capacity |
| ZnO | Zinc oxide |
| $\geq$ | More than equal |
| $\leq$ | Less than equal |
| $>$ | More than |
| $<$ | Less than |

## 1. Introduction

The global poultry industry faces significant challenges in maintaining meat quality during storage. Factors such as temperature control, storage duration, packaging, and microbial growth significantly affect quality. Improper storage temperatures affect microbial spoilage and lipid oxidation, leading to increased drip and cooking losses, impacting tenderness, moisture, and shelf life (Aziz et al., 2020). Prolonged storage increases microbial loads and reduces sensory attributes like flavor and juiciness(Ahmed & Marzany, 2022). Although packaging technologies of absorbent pads, active pullulan, and silver nanoparticles can enhance oxidative stability and moisture retention, they are often inadequate in limiting microbial growth (Hussain et al., 2024; Khan et al., 2022). In addition, traditional preservation methods, including vacuum packaging and synthetic additives, offer limited microbial control and may compromise the nutritional and sensory attributes of meat (Rosario et al., 2021). These factors often interact synergistically, with inadequate packaging and longer storage at suboptimal temperatures exacerbating meat spoilage (Hussain et al., 2024). Growing consumer awareness of food production, particularly ingredients, additives, preservatives, and production methods, has now heavily influenced purchasing decisions. This awareness has driven a gradual increase in demand for transparency and natural ingredients in meat products, to adopt industries, natural preservative strategies aligned with clean-label innovations (Asioli et al., 2017; Thangavelu et al., 2019). As a result, consumer preferences have shifted toward clean-label natural production that avoids artificial additives. Given the perishability of broiler meat, innovative and natural preservation approaches that enhance microbial safety and maintain physicochemical and sensory characteristics are crucial (Aziz et al., 2020; Kim et al., 2020).

As health-conscious consumers reject synthetic preservatives, demand for natural bio-preservation strategies is growing (Abd El-Hack et al., 2022; Lee & Yoon, 2024). Among these, postbiotics, bioactive compounds produced from lactic acid bacteria (LAB), are emerging as effective natural antimicrobials and antioxidants (Guzik et al., 2022). The International Scientific Association of Probiotics and Prebiotics (ISAPP) defines postbiotics as "a preparation of inanimate microorganisms and/or their components that confers a health benefit on the host" (Salminen et al., 2021) referring to non-viable microbial cells or fragments. However, in food science, a broader, metabolite-focused definition is more relevant; understood as cell-free bioactive compounds secreted during fermentation, such as organic acids, fatty acids, bacteriocins, bacteriocin-like inhibitory substances (BLIS), γ-aminobutyric acid (GABA), exopolysaccharides, and peptides (Aguilar-Toalá et al., 2018; Duarte et al., 2024; Wegh et al., 2019). This study adopts this metabolite-based definition, focusing on postbiotics derived from neutralized and concentrated cell-free supernatants (CFS) of LAB strains. These compounds offer antimicrobial, antioxidant, anti-inflammatory, and anti-cancer properties and are promising alternatives to synthetic preservatives (D'Amore et al., 2025; Moradi et al., 2021; Rad et al., 2021). Additionally, LAB-derived postbiotics can enhance poultry meat quality by improving oxidative stability and texture, reducing lipid oxidation, and maintaining flavor and texture (Morán & Kilasoniya, 2024; Torres-Martínez et al., 2022).

Recent studies show that postbiotics-enriched marinades stabilize meat pH, color, and cooking loss by enhancing protein structure, water-holding capacity, and oxidative stability of myoglobin Arrioja-Bretón et al. (2020). Postbiotics can be directly applied to meat or incorporated into packaging systems, offering versatile applications across meat products (Lima et al., 2022; Sharafi et al., 2023). Their efficacy depends on strain type, concentration, formulation used, application method, and meat type (Abdulhussain Kareem & Razavi, 2020; İncili et al., 2021; Rasouli et al., 2021; Sharafi et al., 2023).

Although previous studies have explored the use of lyophilized, concentrated, or semi-purified forms of postbiotics from *Lactobacillus plantarum, L. acidophilus, Pediococcus acidilactici, L. saki, L. curvatus, L. casei, L. salivarius, L. bulgaricus, Enterococcus faecium,* and *Bifidobacterium* spp. applied with chelating agent/bacterial cellulose/alginate to poultry meat, beef, and their products, most have only measured the pH, TBARS values, color, and sensory properties over 6-40 (Arrioja-Bretón et al., 2020; İncili et al., 2021; İncili et al., 2022a; İncili et al., 2022b; Kaynakci, 2025; Sheikhi et al., 2025; Yordshahi et al., 2020). However, the effects of specific neutralized, enzyme-treated, and concentrated postbiotics from GRAS strains like *L. acidophilus* and *Lacticaseibacillus rhamnosus* GG, applied directly to vacuum-packaged broiler breast meat under chilled storage conditions, remain underexplored.

The novelty of this research is to address that gap by applying neutralized and concentrated postbiotics from *L. acidophilus* ATCC 4356 and *Lcb. rhamnosus* GG ATCC 53103, directly to broiler breast meat. These trains were selected for their known antimicrobial and antioxidant activity. The aim of this study was to evaluate the preservative potential of postbiotics obtained from *L. acidophilus* ATCC 4356 and *Lcb. rhamnosus* GG ATCC 53103 by assessing their effects on the physical, chemical, and sensory properties of vacuum-packaged broiler breast meat stored at 4 ± 1°C. The findings aim to provide scientific evidence supporting the use of LAB-derived postbiotics as clean-label alternatives to synthetic preservatives in broiler meat.

## 2. Materials and methods

### 2.1. Bacterial strains, media, and culture conditions

The study used two LABs: *Lactobacillus acidophilus* ATCC 4356 and *Lacticaseibacillus rhamnosus* GG ATCC 53103. These strains were selected for their ability to produce stable and effective postbiotics with organic acid, fatty acid, and small peptides, making them ideal for application in meat preservation. These strains were previously obtained as liquid stocks, kindly obtained from the Faculty of Applied Science, School of Biology, Universiti Teknologi MARA (UiTM), Malaysia. The stock cultures of LAB strains were revitalized in MRS broth by incubating aerobically in an incubator for 24 h at 37°C. Three consecutive bacterial cultures (1% inoculum, v/v) were prepared and adjusted for maximum postbiotic production by anaerobically incubating at 37°C for 48 h. The last cultures were used as experimental inoculum and maintained as frozen stock at −80°C, containing 40% (v/v) glycerol (Păcularu-Burada et al., 2024).

### 2.2. Application of postbiotics on broiler breast meat

#### 2.2.1. Postbiotic preparation

The postbiotic used in this study was prepared according to Ye et al. (2021) with some modifications. An inoculum (2% v/v) of *L. acidophilus* ATCC 4356 and *Lcb. rhamnosus* GG ATCC 53103 was added to 50 mL MRS broth and incubated anaerobically at 37°C for 48 h until an $OD_{600nm}$ of 0.95 was reached. Several studies (El-Mokhtar et al., 2020; Rahman et al., 2025) suggest that a 48-h anaerobic incubation period at 37°C was used for the selected LAB strains, which typically yields maximal levels of bioactive metabolites. Cultures were centrifuged at 10,000 rpm (≈9,500 × g) for 20 min at 4°C, and supernatants were filtered through a 0.22 μm syringe filter to obtain cell-free supernatant (CFS) (Qadi et al., 2023). These were concentrated 10-fold using a rotary evaporator at 60°C for 2 h (Arrioja-Bretón et al., 2020) and stored at –20 °C until use.

#### 2.2.2. Meat and marinade preparation

Fresh raw broiler meat was purchased, obtained within 6 h post-slaughter from a local wet market in Sena Complex, Savar, Dhaka, Bangladesh, and transported (maintained in 4 °C) immediately for experimental procedure. On the same day, breast meat (*Pectoralis major*) was processed; 1 cm was removed from the surface, followed by 15 min of UV treatment to reduce native microbiota (Arrioja-Bretón et al., 2020). The breast meat was sliced into 35 g pieces, each assigned to specific treatments for specific storage days, with three replicates. This size was chosen to ensure analytical precision, manageable replication, and experimental control under lab conditions, with three times repeated trials for validation using 25, 30, and 35 g portions (Serter et al., 2024). The marinades, enriched with concentrated CFS from *L. acidophilus* ATCC 4356 and *Lcb. rhamnosus* ATCC 53103 was formulated according to Arrioja-Bretón et al. (2020) with some modifications. In brief, 0.35% NaCl was prepared in double-distilled water, and 10-fold concentrated CFS of each LAB strain was mixed (Table 1). The marinades were stored in a refrigerator at 40°C before use.

#### 2.2.3. Inoculation of vacuum-packaged broiler meat

Thirty-six breast meat samples were randomly assigned to three treatments (n=3 per group per time point): control, meat soaked with distilled water; LA, meat soaked in postbiotic marinades from *L. acidophilus* ATCC 4356; and LGG, meat soaked in postbiotic marinades from *Lcb. rhamnosus* ATCC 53103. Each meat piece was soaked in the corresponding marinade at a 5:1 ratio (marinade: meat, w/v) for 30 min in a sterile petri dish (Arrioja-Bretón et al., 2020). After marination, samples were vacuum-packed in sterile plastic zip-lock bags and stored at 4°C for 10 days. Physicochemical analyses were performed on days 0, 3, 7, and 10 of storage (İncili et al., 2022a).

**Table 1**
The concentrations of postbiotics of L. *acidophilus* (LA) and *Lcb. rhamnosus* GG (LGG) for the preparation of marinades.

| Items | Marinades concentrations | | |
|---|---|---|---|
| | **Control** | **LA** | **LGG** |
| Sodium Chloride (g) | 0.035 | 0.035 | 0.035 |
| Distilled water (ml) | 10 | 5 | 5 |
| LA; CFS of L. *acidophilus* (ml) | – | 5 | 0 |
| LGG; CFS of *Lcb. rhamnosus* GG (ml) | 0 | 0 | 5 |
| Total amount of marinades (ml) | 10 | 10 | 10 |

LA, Postbiotic of L. *acidophilus* ATCC 4356. LGG, Postbiotic of *Lcb. rhamnosus* GG ATCC 53,103.

### 2.3. Physicochemical quality assessment of meat

#### 2.3.1. pH measurement

The pH of control and postbiotic-treated meat samples was measured on days 0, 3, 7, and 10 using a benchtop pH meter. Before measurements, a three-point calibration was conducted with buffer solutions (pH 4.01, 7.00, and 10.00) at 25°C (AOAC, 2005). Each 5 g sample was homogenized in 45 mL of distilled water, and pH values were recorded using a glass electrode connected to the pH meter. All measurements were done in triplicate at 25°C.

#### 2.3.2. Determination of oxidation stability (TBARS value)

The thiobarbituric acid reactive substances (TBARS) values, an indicator of lipid oxidation in broiler breast meat samples, were determined using a modified method from Fan et al. (2021). Meat samples (4 g) were homogenized in 10 mL of 20% trichloroacetic acid for 1.5 min. After 15 min of incubation at 25°C, de-ionized water (10 mL) was added, and the mixture was filtered through the Whatman 6 filter paper. A 5 mL aliquot of the filtrate was mixed with 5 mL of 0.005 M 4,6-dihydroxy-2--mercaptopyrimidine and heated at 80 ± 1°C using a water bath (Memmert WNB-14, Germany) for 30 min, then cooled and incubated at 25°C for 20 min. The supernatant was separated, and absorbance was checked by a UV–VIS spectrophotometer (UV-1800) at 530 nm wavelength against a blank without a sample. The malondialdehyde concentration (mg MDA/kg of meat) was calculated from a standard curve and reported as TBARS values.

#### 2.3.3. Drip loss (%) and water-holding capacity (%)

The treated and control broiler meat's water-holding capacity (WHC) was determined based on the drip loss and cooking loss percentage after the respective storage periods. Drip loss percentages (DL %) of meat samples were calculated according to the methodology reported by Sarkar et al. (2024), with minor modifications. After refrigerating at 4 ± 1°C for 0, 3, 7, and 10 days, five meat samples (n = 5) of approximately 5 g each were taken from each treatment group (Control, LA, and LGG) every storage day. The samples were removed from their vacuum-sealed polyethylene bags for analysis, weighed, and recorded as initial weights such as $W_i$. The weighted meat samples were placed in Ziplock polyethylene bags, properly labeled, vacuum-packed, and stored at 4°C for 24 h. After storage, the meat samples were removed from the bags, lightly dapped with paper towels, reweighed, and recorded as $W_f$. The following formula was used to determine the percentage of DL (Honikel, 1998) (Formula (1)):

$$DP\ \% = \left[\frac{W_i - W_f}{W_i}\right] x100 \tag{1}$$

The WHC of broiler breast meat samples at 0, 3, 7, and 10 storage days was measured using the following Formula: (2).

$$WHC\ \% = 100 - \left(\left[\frac{W_i - W_f}{W_i}\right] x100\right) \tag{2}$$

Where $W_i$ represents the initial weight of meat at each storage day (g), and $W_f$ represents the final weight of meat samples at the same storage day (g).

*2.3.4. Cooking loss determination*

Five meat samples (n = 5), with an average weight of 5.0 g, were sampled from each storage period, vacuum-packed, and stored at 4 ± 1 °C to estimate cooking loss (CL, %). The meat samples were removed from the freezer, gently dapped with paper towels, and weighed ($W_i$). The samples were then cooked in a preheated water bath at 80°C for 30 min. After 30 min, when the internal temperature of the meat reached 78°C, as shown by a stabbing probe thermometer, the meat was allowed to cook for another 10 min to ensure all samples achieved the same internal temperature. After that, the meat samples were removed from the water bath, allowed to cool down to room temperature, removed from the plastic bag, carefully dapped dry with paper towels without being squeezed, and re-weighed ($W_f$) after 24 h (Honikel, 1998). On days 0, 3, 7, and 10, the CL (%) was calculated as per the methodology of Schwarz et al. (2019) in the following equation (Formula (3)).

$$CL\ \% = \left[\frac{W_i - W_f}{W_i}\right] x100 \tag{3}$$

Where *Wi* is the muscle sample weight before cooking in the water bath (g), and *Wf* is the muscle sample weight after cooking in the water bath (g).

## 2.4. Color determination of broiler meat

For the color assessment, meat samples measuring 2 cm × 2 cm × 1 cm and weighing approximately 10 g were obtained from stored broiler samples. After removing the packaging, three observations per sample were recorded at three random points, following Noori et al. (2018), and the average represented each color parameter. A Color Reader spectrophotometer (China) was used to determine the International Commission on Illuminance Lab-values of CIE L* (lightness), a* (redness), and b* (yellowness) values, calibrated against black and white tiles before analysis. In addition to L*, a*, and b*, chromatography (ΔE), chroma (C), and hue (H) were calculated. The samples at 0 days of storage served as the 'standard (s)'. The equations to calculate chromatography (ΔE), chroma (C), and hue (H) are as follows (formulas 4, 5, and 6). The L* value measures brightness (0 to 100); a* ranges from −120 to +120 for greenness/redness, and b* measures blueness/yellowness. For each sample, three measurements were taken, and the average of the three readings was used to represent the value of each color parameter.

$$Chromatogrphy\ (\Delta E) = \sqrt{(L^* - L^s)2 + (a^* - a^s)2 + (b^* - b^s)2} \tag{4}$$

where $L^s$, $a^s$, and $b^s$ represent the lightness, yellowness, and redness of standard meat samples from the control group at day 0 of storage.

$$Chroma\ (C) = \sqrt{(a^*)^2 + (b^*)^2} \tag{5}$$

$$Hue\ (H) = \tan^{-1}\left(\frac{b^*}{a^*}\right) \tag{6}$$

## 2.5. Texture profile analysis of broiler meat

Texture profile analysis (TPA) was performed following the method described by Asyrul-Izhar et al. (2021) after each sampling day (0, 3, 7, and 10 days), using a CT3 Texture Profile analyzer equipped with an AACC36 compression probe. The instrument was calibrated with a 5 kg load cell, 5 mm deformation, 10 mm/s return speed, and a 10 g contact force. Samples weighing 10 g each were positioned for double compression at 50% strain. Five samples per treatment were analyzed, and hardness, cohesiveness, springiness, gumminess, and chewiness were recorded in triplicate.

## 2.6. Sensory evaluation of broiler meat

Sensory evaluation was carried out according to the method described by Chakchouk-Mtibaa et al. (2017), with cooking steps modified from Hayat et al. (2024) and Roslan et al. (2019). There were 30 individuals from BLRI, Dhaka, who evaluated the sensory attributes of postbiotic-treated broiler meat. Each panelist was requested to mention levels of odor (rancidity or agreeable), texture (soft or hard), color (golden brown to pale), and overall acceptability of broiler meat (with or without the postbiotics addition) that was stored at 4 °C. The judges were unaware of the experimental approach, with samples blindly assigned as A (control), B (LA postbiotic), and C (LGG postbiotic). Thirty judges were randomly assigned to each sample, with ten per group. A 5-point hedonic scale was employed where 1 = very poor, 2 = poor, 3 = moderately good, 4 = very good, and 5 = best desirable attribute. The cooked meat samples for each treatment group were cut into (1.5 × 1.5 × 1.5 cm) cubes before being served warm to the panelists (Roslan et al., 2019). The meat treated with postbiotics was assessed for sensory attributes at 0, 7, and 10 days of storage by panelists.

## 2.7. Statistical analysis

Statistical analyses were conducted using SPSS software version 25.0 for Windows (SPSS, Inc., Chicago, IL, USA). One-way analysis (ANOVA) and Duncan's Multiple Range Test (DMRT) at a 95% confidence level ($p < 0.05$) were used to evaluate the significant difference among independent groups of pH, cooking loss, water holding capacity, drip loss, TBARS value of meat, color, texture, and sensory properties of marinated meat samples (Steel et al., 1997). Results were reported as mean ± standard error of the mean (SEM). Furthermore, a two-way ANOVA using the General Linear Model (GLM) procedure was also performed to test the interaction effect of storage duration (0, 3, 7, and 10 days) and postbiotic treatments (LA and LGG) on physicochemical parameters, instrumental color, and texture profiles of meat. To further interpret the correlation variables (Spearman correlation coefficient) and visualize sample grouping, multivariate analysis of Principal Component Analysis (PCA) and Hierarchical Cluster Analysis (HCA) was conducted.

# 3. Results and discussions

## 3.1. Effect of postbiotics on meat physicochemical properties

Postbiotics, the bioactive compounds produced during fermentation by beneficial LAB strains, play a significant role in enhancing the physicochemical properties of meat. Their incorporation into meat and meat products improves microbial stability, shelf life, and antioxidant capacity, and maintains the meat's external and internal quality (Ozma et al., 2023).

*3.1.1. The pH values in broiler meat*

The pH of broiler meat significantly influences its biochemical properties, texture, and sensorial attributes (Chaparro-Hernández et al., 2019). Typically, broiler meat pH ranges from 5.5-6.79, where values below 5.8 indicate PSE (Pale, Soft, and Exudative meat), 5.9-6.2 are standard, and above 6.3 denote DFD (Dark, Firm, and Dry) meat (de Carvalho et al., 2018). In this study, postbiotics from LA and LGG significantly ($p < 0.01$) influenced pH over 10 days of refrigerated storage (4 ± 1 °C), while initially the values ranged from 5.99 to 6.37, as shown in Table 2. These fluctuations are influenced by the protein and the initial pH of the meat (Mennah-Govela et al., 2020; Tan et al., 2014). LA and LGG postbiotics-treated meat samples showed a steady decrease in pH, with LA dropping from 6.16 to 6.04 and LGG from 6.11 to 6.03 by day 10. In contrast, the control group maintained higher pH values, decreasing from 6.37 to 6.30. The notable decrease in pH is attributed to the presence of LAB-derived organic acids (e.g., lactic, acetic, butyric) produced during carbohydrate fermentation, which acidifies the meat matrix (Bangar et al., 2022). Additionally, the acidification might be achieved by other acidic metabolites such as fatty acids (palmitic acid, stearic acid, myristic acid, oleic acid, linoleic acid, and alpha-linolenic acid), peptides, or phenolic compounds that are also released from LAB during fermentation (Lim et al., 2018; Rahman et al., 2025; Wong et al., 2015). These acids, collectively known as antimicrobial postbiotics, accumulate in meat, thereby lowering the meat pH. In control meat, slightly higher pH values indicated that the spoilage was due to protein denaturation, which produces amino acids and leads to the formation of ammonia and amines, resulting in alkaline reactions (Chakchouk-Mtibaa et al., 2017). Our finding aligns with previous research indicating LAB-derived postbiotics effectively reduce pH and extend the shelf life of perishable food items (Kaveh et al., 2023; Lahiri et al., 2022) up to 14 days of storage. Similarly, postbiotics of different LAB strains variably reduced the pH values of meat, chicken drumsticks, chicken frankfurters, and chicken sausages found in other studies (Dong et al., 2020; İncili et al., 2021, İncili et al., 2022a; Segli et al., 2021; Sheikhi et al., 2025; Tirado-Gallegos et al., 2021). However, discrepancies with studies showing no effect of the pH values of chicken breast fillets and drumsticks when immersed in postbiotics for 3 min and stored for six days (İncili et al., 2021, İncili et al., 2022a). The difference between their findings and the current results may be attributed to the shorter marination time of the postbiotics with meat. The results highlight the role of postbiotics, especially LA and LGG, in extending meat shelf life and safety by lowering pH over 10 days, indicating their potential to preserve meat quality.

#### 3.1.2. Determination of lipid oxidation in broiler meat

Lipid peroxidation in broiler meat, indicated by TBARS production, provides a measure of oxidative stability during storage (Vital et al., 2018). This harmful byproduct, produced from oxidation, can negatively affect the taste of processed meats. Thus, literature suggests that oxidation of meat lipids may be reduced by antimicrobial agents like postbiotics (Chakchouk-Mtibaa et al., 2017). In this study, postbiotics from LA and LGG significantly affected TBARS levels during 10 days of refrigerated storage of broiler meat at (4 ± 1 °C), as shown in Table 3. Initially, TBARS values were similar among groups ($p = 0.210$), but levels increased significantly ($p < 0.001$) over time, with control samples showing the highest oxidation (0.286 to 0.829 mg MDA/kg). This observation underscores the oxidative deterioration of broiler meat caused by the accumulation of nitrogen-containing components such as ammonia and amines, resulting from lipid peroxidation, autolytic enzymatic reactions, and proteolytic activity over time (Dimov, 2022; Ebadi et al., 2019). In contrast, LA and LGG treatments exhibited lower TBARS levels by day 10 (0.694 and 0.678 mg MDA/kg, respectively), indicating better oxidative stability ($p < 0.05$). This pattern reflects the protective role of postbiotics in reducing lipid oxidation, likely due to their bioactive metabolites such as organic acid, peptides, and antioxidant compounds (Mabrouk et al., 2024). These findings align with (Chakchouk-Mtibaa et al., 2017; Kaynakci, 2025), who found that the postbiotics of *E. faecium* and *Bifidobacterium* spp. reduced TBARS values in turkey meat stored up to 14 days. The researchers also stated that the control sample had a TBARS value of 0.96 mg MDA/kg with an unpleasant odor, while the treated samples stayed lower at 0.7 mg MDA/kg after 7 days. Similarly, Smaoui et al. (2016)observed delayed primary and secondary oxidation in chilled turkey meat sausages treated with bacteriocin BacTN635. In addition, İncili et al. (2021) reported that TBARS values increased in all postbiotics-treated groups in broiler breast fillets; however, the meat treated with 50% postbiotics of *Pediococcus acidilactici* exhibited the lowest values. To our knowledge, no comparative study has thoroughly investigated the impact of postbiotics on the TBARS values in broiler breast meat. Recently, researchers used the maximum permissible limit of MDA concentrations between 1-2 mg of MDA per kg as threshold values for acceptable rancid meat and meat products (Khorshidi et al., 2021; Saricaoglu & Turhan, 2019). Therefore, in this study, none of the broiler breast meat samples exceeded this limit, though slight increases in MDA levels were observed during storage, ranging from 0.678 to 0.829 mg MDA/kg. De Abreu Martins et al. (2021) stated that consumers can detect rancidity at concentrations greater than 0.5 mg of MDA, highlighting that this amount can greatly affect perceived freshness in meat. In the current findings, no meat samples exceeded this level during seven days of storage, likely due to the combined antioxidant effects of NaCl and postbiotics (İncili et al., 2022b). In line with the current results, the literature (Chattopadhyay et al., 2019; Firuzi et al., 2019; Sharma et al., 2021) shows significant increases in TBARS values, likely due to higher levels of native LAB and psychrotrophic bacteria in broiler meat, leading to MDA decomposition. LGG postbiotics were more effective than LA in reducing TBARS values, suggesting their potential as natural preservatives to improve meat quality and shelf life.

#### 3.1.3. Drip loss percentage of broiler meat

Drip loss in meat is a key indicator of meat quality, influenced by factors such as external temperature, storage methods, and vacuum packaging (Carballo et al., 2017; Mir et al., 2017). In this study, the effects of LA and LGG postbiotics on drip loss in broiler meat over 10 days of refrigerated storage are shown in the boxplot (Fig. 1A) and Supplementary Table S1. At day 0 (fresh meat), all samples showed comparable drip loss percentages (1.93 to 2.14%), with no significant difference ($p = 0.325$). However, from 3 to 10 days, control meat showed a significant increase in drip loss, rising from 2.47 to 3.02% ($p < 0.001$), consistent with previous reports of linking muscle protein denaturation, specifically the transition from α-helices to β-sheets, and WHC loss to storage (S. Zhu et al., 2025). In contrast, meat treated with

**Table 2**
The effect of postbiotics of L. *acidophilus* (LA) and *Lcb. rhamnosus* GG (LGG) on the pH of broiler meat stored for up to 10 days.

| Storage | Treatment | | | P-value |
|---|---|---|---|---|
| | Control (SEM) | LA (SEM) | LGG (SEM) | |
| 0 day | $6.37{\pm}0.04^{a,x}$ | $6.16{\pm}0.02^{b,x}$ | $6.11{\pm}0.02^{b,x}$ | 0.002 |
| 3 days | $6.21{\pm}0.02^{a,y}$ | $6.12{\pm}0.01^{b,y}$ | $5.99{\pm}0.03^{c,x}$ | 0.001 |
| 7 days | $6.30{\pm}0.02^{a,xy}$ | $6.04{\pm}0.01^{b,z}$ | $6.03{\pm}0.07^{b,x}$ | 0.007 |
| 10 days | $6.28{\pm}0.02^{a,xy}$ | $6.03{\pm}0.01^{b,z}$ | $6.04{\pm}0.03^{b,x}$ | 0.010 |
| P-value | 0.021 | 0.000 | 0.291 | |

$^{abc}$ Different superscript letters within the same row differ significantly ($P \leq 0.05$) between treatments. $^{xyz}$ $^{D}$ifferent superscript letters within the same column differ significantly ($P \leq 0.05$) among the storage periods. Means are presented as SEM (standard error of the mean). LA, Postbiotic of L. *acidophilus* ATCC 4356. LGG, Postbiotic of *Lcb. rhamnosus* GG ATCC 53,103.

**Table 3**
The effect of postbiotics of L. *acidophilus* (LA) and *Lcb. rhamnosus* GG (LGG) on the TBARS value of broiler meat stored for up to 10 days.

| Storage | Treatment | | | P-value |
|---|---|---|---|---|
| | Control (SEM) | LA (SEM) | LGG (SEM) | |
| 0 day | $0.286{\pm}0.002^{a,z}$ | $0.275{\pm}0.004^{a,z}$ | $0.276{\pm}0.006^{a,z}$ | 0.210 |
| 3 days | $0.298{\pm}0.005^{b,z}$ | $0.371{\pm}0.025^{a,y}$ | $0.281{\pm}0.008^{b,z}$ | 0.013 |
| 7 days | $0.471{\pm}0.003^{a,y}$ | $0.433{\pm}0.003^{b,y}$ | $0.443{\pm}0.009^{b,y}$ | 0.007 |
| 10 days | $0.829{\pm}0.001^{a,x}$ | $0.694{\pm}0.010^{b,x}$ | $0.678{\pm}0.006^{b,x}$ | 0.000 |
| P-value | 0.000 | 0.000 | 0.000 | |

$^{abc}$ Different superscript letters within the same row differ significantly ($P \leq 0.05$) between treatments. $^{xyz}$ Different superscript letters within the same column differ significantly ($P \leq 0.05$) among the storage periods. Means are presented as SEM (standard error of the mean). T: treatment; S: storage period. LA, Postbiotic of L. *acidophilus* ATCC 4356; LGG, Postbiotic of *Lcb. rhamnosus* GG ATCC 53,103.

postbiotics LA and LGG displayed a non-significant increase in drip loss, from 2.04 to 2.38% for LA postbiotics and 2.32 to 2.46% for LGG postbiotics. LA postbiotics-treated broiler meat showed significantly ($p < 0.05$) lower drip loss than control (3.02%) and LGG on day 10, indicating improved water retention. Additionally, the lower drip loss in postbiotics-treated broiler meat samples may be attributed to organic acids or other antioxidant metabolites that stabilize muscle protein or cell membranes (H. Li et al., 2024; Rossoni et al., 2024).

#### 3.1.4. Water holding capacity of broiler meat

The WHC significantly influences meat juiciness, tenderness, and overall consumer eating experience (Hayat et al., 2024). Fig. 1B (boxplot) and Supplementary Table S2 show the effect of LA and LGG postbiotics on the WHC of broiler meat stored at 4 ± 1°C for 10 days. At day 0, WHC values (66.63-67.48 %) did not differ significantly between treatments ($p = 0.332$). However, a significant treatment effect ($p < 0.01$) emerged from day 3 onwards, with the control sample showing a notable reduction in WHC to 59.94 % by day 10, while LA and LGG postbiotics effectively ($p < 0.05$) increased WHC to 73.09 % and 71.01 %, respectively. WHC in the control samples decreased substantially over 10 days of storage, likely due to the breakdown of protein structure, higher lactic acid production resulting from glycolysis, lowering pH, and causing charge shielding, which ultimately reduced the water-binding capacity of meat (Ji et al., 2024). LGG postbiotics-treated meat samples exhibited the notably ($p <0.05$) highest WHC on day 3 (69.52 %), while LA postbiotic-treated meat demonstrated superior WHC by days 7 and 10 (72.30 % and 73.09 %, respectively). Postbiotics appeared to preserve WHC, which is likely due to bioactive compounds like organic acids, peptides, lipids, and antioxidants that stabilize meat protein, preserve muscle fiber integrity, and reduce oxidative damage, improving the meat's water retention (Ji et al., 2024). In line with the present findings, Kaynakci (2025), reported a slightly higher WHC (85-95%) of turkey meat treated with postbiotics of *Bifidobacterium* spp. stored for 7 days. The inclusion of NaCl in this experiment as a marinade likely enhances these effects. NaCl solubilizes myofibrillar proteins and supports gelation and fat retention during heating, contributing to improved WHC, flavor, and microbial stability (Wang et al., 2023; Warner, 2022). In addition, studies showed that (Albuquerque et al., 2019) organic acids and their salts display further functionalities as biotechnological agents for enhancing physicochemical properties and improving sensory attributes of meat and meat products. Masoumi et al. (2022) indicated that at pH values below or above the isoelectric point, the net charge of most proteins becomes negative or positive, leading to increased WHC. However, the reduction of WHC negatively impacts meat quality and can lead to economic suffering from moisture loss during storage and cooking (Mir et al., 2017). Overall, postbiotics, especially from LA, effectively improved WHC, supporting their use as natural meat quality enhancers to reduce moisture loss, increase tenderness, and extend shelf life.

#### 3.1.5. Cooking loss (%) of broiler meat

Meat cooking loss refers to the weight and moisture lost during cooking, which significantly impacts the yield, quality, appearance, and acceptance of broiler meat (Mueller et al., 2023). Various elements, such as the cooking method, temperature, cooking time, and the initial characteristics of the meat, contribute to this natural occurrence (Hayat et al., 2024). The effect of postbiotics from LA and LGG on the cooking loss of broiler breast meat stored for up to 10 days is illustrated in the boxplot (Fig. 1C) and Supplementary Table S3. At day 0, no significant differences ($p = 0.075$) were observed among the treatments, with cooking loss values ranging from 25.69-27.45 %. However, storage significantly affected cooking loss over time. The control group showed the highest increases, reaching 35.03% on day 10, while LA postbiotics-treated meat exhibited the lowest cooking loss (29.45%, $p < 0.05$). LGG postbiotics-treated samples had an intermediate value at 32.65%. Similar trends were reported by Masoumi et al. (2022), where probiotic yogurt (*L. casei*) significantly reduced the cooking loss of raw chicken fillets by 48 % and 44 % during the 9 days of storage, with the control group having the highest cooking loss. In the current study, postbiotics consistently reduced cooking loss on days 7 and 10, suggesting stronger protective effects during extended storage. LGG postbiotics showed a viable response, but still reduced losses compared to the control. The reduction in cooking loss may be attributed to peptides, organic acids, and antioxidant compounds in the postbiotics, which stabilize muscle protein, particularly of sarcoplasmic proteins, reduce water retention from oxidative stress and enzymatic activity, and limit denaturation during cooking (Hosseinzadeh et al., 2025). Additionally, NaCl, fatty acids, and organic acids in postbiotics-enriched marinades may alter the meat protein's isoelectric point (IP ~ 5.5), contribute to improved WHC and reduced cooking loss in postbiotics-treated samples during treatment (Fadiloğlu & Serdaroğlu, 2018; Serdaroğlu et al., 2024). Overall, LA postbiotics were most effective in minimizing cooking loss, indicating their potential as bio-preservatives to enhance meat yield, tenderness, and sensory quality. Table 4 summarizes the interactive effect of treatments (control, LA, and LGG) and storage periods (0, 3, 7, and 10 days) on cooking loss as well as on pH, drip loss, WHC, and TBARS value.

### 3.2. Effect of postbiotics on color properties of broiler meat

Meat color is an important quality attribute that affects consumer acceptance and can indicate the freshness and quality of the food (Benli & Yildiz, 2023). Broiler breast meat is typically lighter, with lower redness and yellowness values due to lower myoglobin content. In addition, it has been shown that when pH decreases, myoglobin is easily oxidized to metmyoglobin, resulting in the color of meat with lower intensity (Mir et al., 2017). However, vacuum packaging and cooling can maintain the redness, yellowness, and bright color of broiler breast meat by reducing or slowing the oxidation of myoglobin (M. Zhang et al., 2021). In the present study, LA and LGG postbiotics influence the color values of broiler breast over 10 days of chilled storage, as visualized in Figs. 2 and Supplementary Table S4. The bar graph (Fig. 2 A and F) shows the significant effects of treatment (control, LA, and LGG) and storage duration (0, 3, 7, and 10 days) on broiler breast meat color properties, while the heatmap (Fig. 2G) visualizes the clustering of color parameters across treatments and storage times. The biplot (Fig. 2H) of the Principal Components Analysis (PCA) condenses the multidimensional color data into two main components, emphasizing key trends and groupings.

#### 3.2.1. Lightness (L*) value of broiler breast meat

Lightness (L*) is a critical color parameter reflecting the visual appeal and freshness of broiler meat, directly influencing consumer acceptance. In this study, the lightness (L*) values of broiler breast meat ranged from 46.66 to 54.38 (Fig. 2A), consistent with the values reported by Li et al. (2015). According to Lee et al. (2022), broiler breasts can be categorized based on Lightness (L*) values as lighter (L* 56), normal ($50 < L^* < 56$), and darker ($L^* < 50$). The control broiler breast meat in this study fell within the normal range (50.57-54.38, a dark to light tint) throughout storage, though it exhibited a significant increase in lightness by day 10 ($p < 0.001$). This increase is likely due to oxidative changes, such as the conversion of myoglobin to metmyoglobin, which commonly occurs during extended refrigerated storage and leads to lighter and less desirable meat color (Bernardez-Morales et al., 2024). Conversely, the L* values of broiler meat significantly decreased ($p<0.05$) during storage with 50% LA and LGG postbiotics-enriched marinades, remaining between 46.66 and 52.11. On day 10, LGG postbiotics-treated meat samples had the lowest L* (46.66, $p < 0.01$), indicating that LGG postbiotics effectively reduced discoloration, resulting in a darker color of broiler meat during storage. This color preservation effect may be attributed to the acidifying action of organic acids in the postbiotics, which lowers the pH, stabilizes myoglobin in its

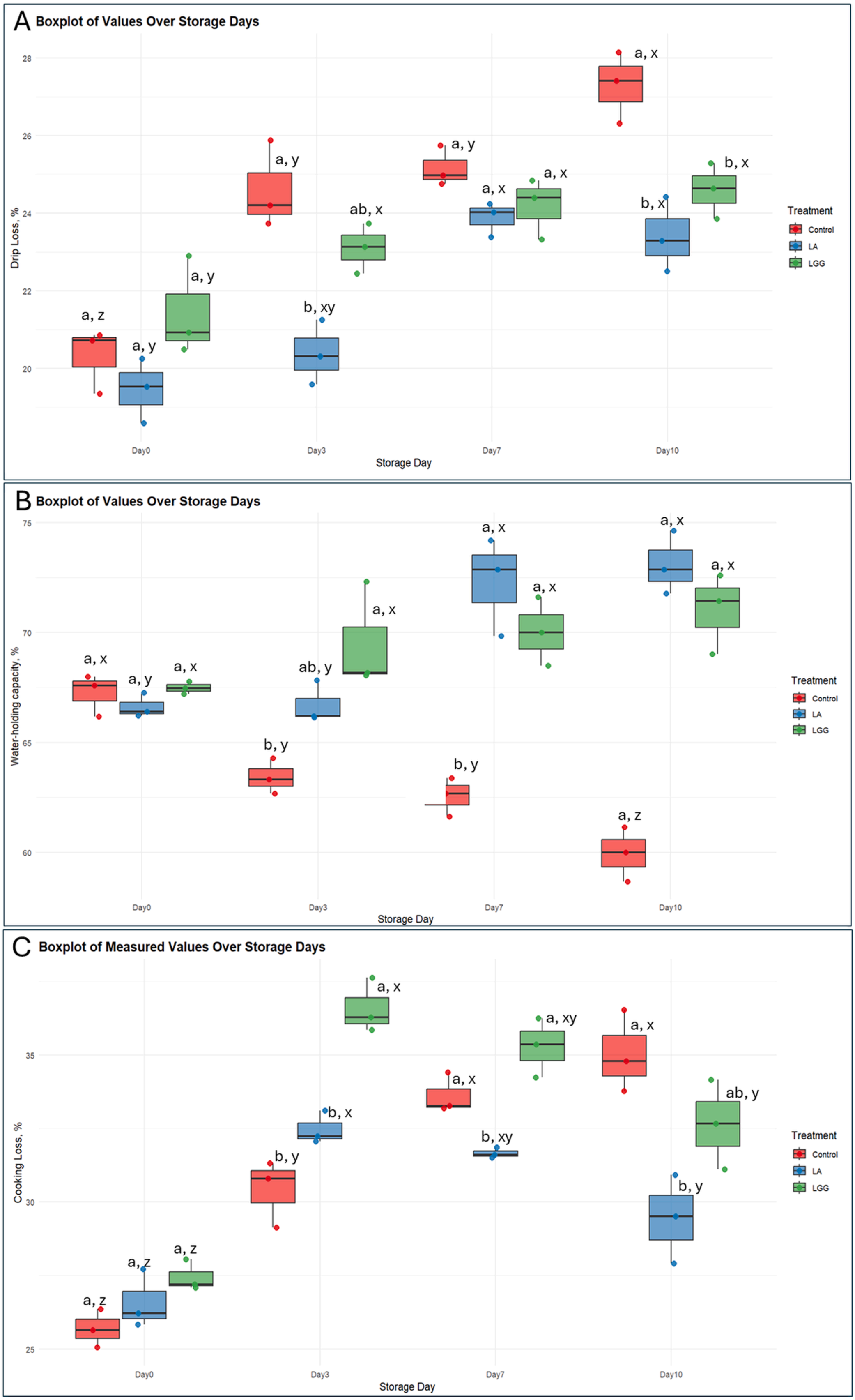


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**Fig. 1.** Boxplots illustrate the changes in (A) drip loss (DL, %), (B) water-holding capacity (WHC, %), and (C) cooking loss (CL, %) over the 10-day storage for three treatments: control (red), LA (blue), and LGG (green). In panels A, B, and C, different lowercase letters (a, b, c) within the same storage days differ significantly ($p < 0.05$; Duncan's test) between treatments. In panels A, B, and C, different lowercase letters (x, y, z) among the same treatment differ significantly ($p < 0.05$; Duncan's test) between storage periods. Means are presented as SEM (standard error of the mean). LA, Postbiotic of L. *acidophilus* ATCC4356; LGG, Postbiotic of Lcb. rhamnosus GG ATCC 53,103.

**Table 4**
Different treatments (control, LA, and LGG) and storage periods (0, 3, 7, and 10 days) affect the physicochemical properties of broiler breast meat.

| ANOVA (P-value) | pH | Drip loss | WHC | Cooking loss | TBARS value |
|---|---|---|---|---|---|
| Main effect | | | | | |
| Treatment (T) | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| Storage (S) | 0.000 | 0.000 | 0.055 | 0.000 | 0.000 |
| 2-way interactions | | | | | |
| T X S | 0.148 | 0.103 | 0.072 | 0.057 | 0.005 |

TBARS, Thiobarbituric acid reactive substance; WHC, Water-holding capacity. LA, Postbiotic of L. *acidophilus* ATCC4356; LGG, Postbiotic of *Lcb. rhamnosus* GG ATCC 53,103.

reduced form, and slows down the oxidative discoloration (Arrioja-Bretón et al., 2020; Zhang et al., 2021). Additionally, vacuum packaging and chilled storage (4 ± 1 °C) may contribute to maintaining meat color by limiting oxygen exposure. Similar reductions in lightness due to the postbiotic treatment have been observed in earlier studies. Arrioja-Bretón et al. (2020) and Segli et al. (2021) reported that raw beef pieces and vacuum-packaged meat discs treated with marinades enriched with postbiotics from *L. plantarum* NRRL B-4496, *L. acidophilus* CRL641, and *L. curvatus* CRL705 developed darker and brownish coloration during storage. İncili et al. (2021) also demonstrated that postbiotics mixed with chitosan applied to chicken breast fillet led to decreased L* values after 12 days, while 50% postbiotics-treated samples decreased from 58.51 to 49.35 in 15 days. In another study, İncili et al. (2022a) showed that the postbiotics from *Pediococcus acidilactici* and *Latilactobacillus sakei/Staphylococcus xylosus* did not significantly alter the color of chicken drumsticks. These findings suggest that postbiotics can modulate meat surface color, especially under vacuum packaging. Discrepancies in lightness (L*) values among studies observed in broiler breast meat may result from differences in pH level of postbiotics, the methods used for their application, postbiotics preparation media, and the specific types of meat involved (İncili et al., 2022a). Moreover, the darker tint in postbiotic-treated meat could stem from the amber color of the antimicrobial bioactive substances themselves (Beristain-Bauza et al., 2017) and the composition of marinades tested (Gargi & Sengun, 2021). Collectively, these results confirm that postbiotics from LA and LGG may help preserve the natural appearance of broiler meat by minimizing oxidative color changes during chilled storage.

### 3.2.2. Redness (a*) value of broiler breast meat

The redness (a*) values are an important color parameter reflecting meat freshness and consumer appeal. In this study, the a* values of broiler breast meat ranged from 1.62 to 3.80 (Fig. 2B), aligning with the pervious reported range of 1.25 to 3.89 (Chakchouk-Mtibaa et al., 2017). At day 0, the* values were statistically similar across the treatments ($p = 0.219$), indicating that the initial color of the meat was not affected by the postbiotics. However, as storage progressed, significant differences emerged. Postbiotics-treated meat samples, particularly those with LA and LGG, retained higher redness compared to the control, suggesting improved color stability. The highest value (3.80) was observed in LGG-treated samples on day 3, followed by LA postbiotics (2.79) ($p < 0.001$), though the postbiotics-treated meat samples significantly increased a* values on day 7 ($p < 0.01$) and 10 ($p < 0.001$). Vacuum packaging and chilled storage (4 ± 1 °C) likely contributed to preserving the red color in postbiotic-treated meat by limiting oxygen exposure and slowing pigment oxidation (Zhang et al., 2021). In contrast, control samples showed a continuous decline in a* values, reaching the lowest point (3.07 to 1.68, $p < 0.001$) on day 10. Without any biochemical treatment, this reduction in redness is commonly linked to the oxidation of myoglobin into metmyoglobin during storage, leading to color fading (Amaral et al., 2018; Dimitrov et al., 2023). Arrioja-Bretón et al. (2020) found that marinades with postbiotics from *L. plantarum* significantly preserved redness in fresh beef. Although Gargi and Sengun (2021) and Soysal et al. (2015) reported higher a* values in chicken treated with various antimicrobial agents or probiotic marinades, variation in meat type, treatment composition, and storage conditions may explain these differences. In contrast, (İncili et al., 2022a, 2022b) found that postbiotics and chitosan did not affect the color properties of a* value in the chicken breast fillet at early storage days, differences emerged depending on treatment concentrations and their combinations over time (15 days). The relatively higher redness a* value in LGG postbiotics-treated meat samples indicates stronger protection against oxidative changes (reduced myoglobin oxidation), likely due to the antioxidant activity of LGG postbiotic components. These compounds may help prevent lipid and pigment oxidation, thereby preserving the meat's reddish hue and enhancing its visual appeal over storage.

### 3.2.3. Yellowness (b*) value of broiler breast meat

Yellowness (b*) is an important visual quality attribute in poultry meat, impacting consumer perception of freshness. In the present study, the b* values of broiler breast meat ranged from 13.62 to 16.95 (Fig. 2C), while this value remained comparable across the treatments at 0 ($p = 0.366$) and 3 days ($p = 0.413$). However, significant differences emerged after 7 and 10 days of refrigerated storage (4 ± 1°C). Postbiotics-treated meat samples with LA and LGG showed higher b* values, 16.46 and 14.61 ($p < 0.01$) on day 7, and 16.32 and 16.95 ($p < 0.05$) at day 10, compared to the control ($p = 0.338$). The elevated b* values in postbiotic-treated meat can be linked to delayed lipid oxidation, less denaturation of myoglobin pigments, and surface dehydration, contributing to increased yellow pigmentation during storage (Yue et al., 2024). In contrast, the control group showed comparatively lower b* values, potentially due to microbial spoilage, particularly *Pseudomonas* spp., which creates slime and reduces metmyoglobin to deoxymyoglobin, leading to discoloration. Postbiotics are known to possess antioxidant properties, which help stabilize lipids and pigments, reduce oxidative degradation, and contribute to color preservation (Doski & Kareem, 2023a; Humam et al., 2020). Furthermore, acidification of the meat matrix by probiotics in marinades, as indicated by lower pH values, may enhance yellowness, as acidic conditions can increase the b* parameter (Kaynakcı, 2024). Consistent with the current findings, Soysal et al. (2015) reported increased b* values (7.87 and 13.67) in chicken drumsticks treated with nisin coupled with low-density polyethylene and stored at 5°C for 6 days. Similarly, (Gargi & Sengun, 2021) observed b* value between 11.72 to 13.11 in uncooked meat treated with probiotic-enriched marinades. Arrioja-Bretón et al. (2020) also discovered that marinades containing postbiotics from *L. plantarum* significantly changed the b* values in fresh beef during storage. However, other studies showed limited or no changes in b* values following postbiotics application. For example, Incili et al. (2020, 2022b) found that short immersion duration of various concentrations of postbiotics derived from LAB combination with chitosan did not significantly affect the b* values in chicken breast fillets and frankfurters stored up to 35 days. Similar findings were stated for various meats such as frankfurters, sausages, turkey sausages, vacuum-packed sausages, and chicken breast

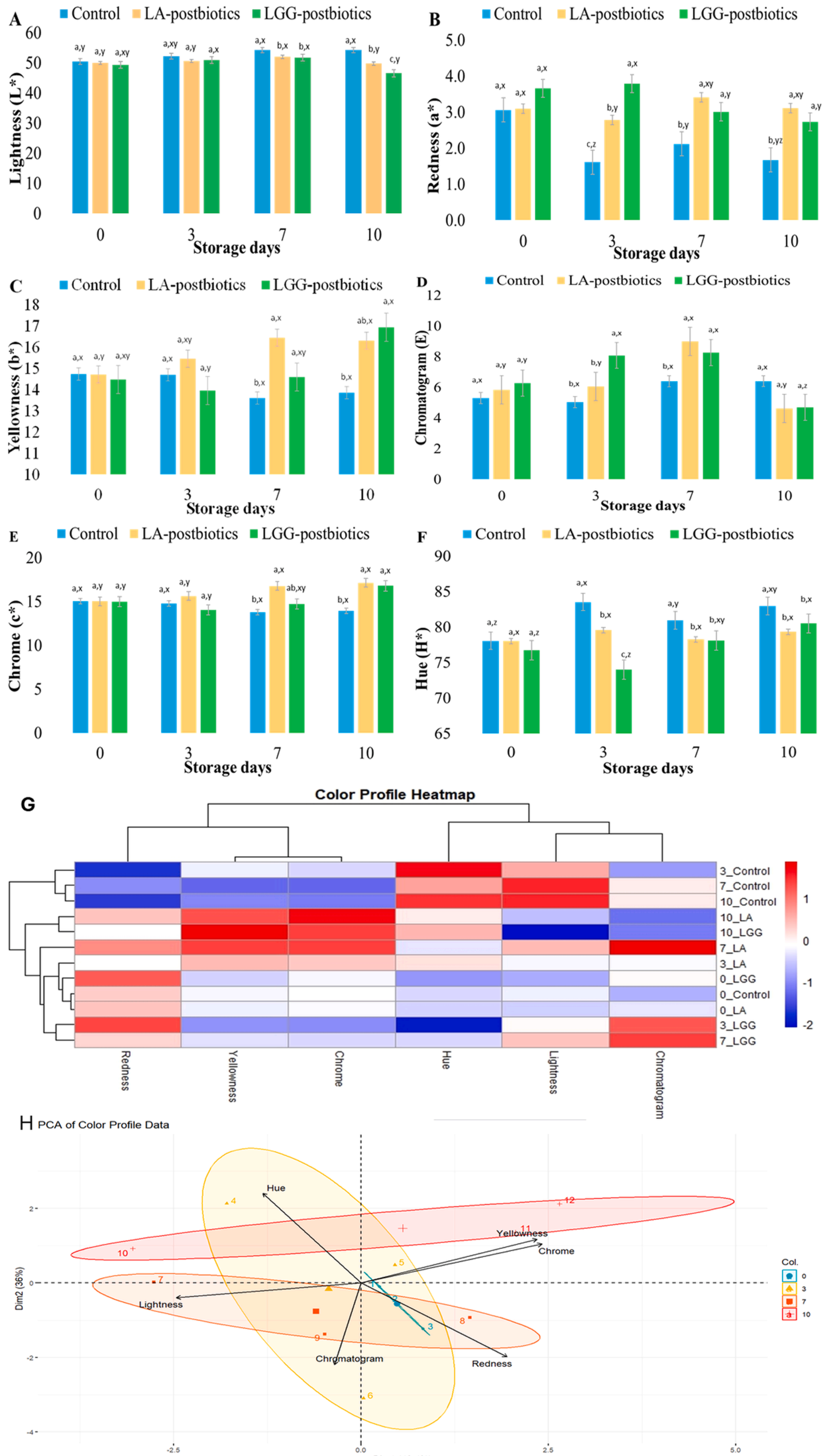


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**Fig. 2.** Effect of treatments (control, LA, LGG) on the color properties of broiler meat stored for 0, 3, 7, and 10 days. The bar graphs (A-F) show changes in individual color traits: (A) lightness, (B) redness, (C) yellowness, (D) chromatogram, (E) chroma, and (F) Hue values over time. Panel (G) presents a heatmap illustrating hierarchical clustering (HCA) of color profile data across all treatment and storage days. Panel (H) displays principal component analysis (PCA) color profile data to visualize overall variation and clustering based on treatments and storage time. PCA reduces multidimensional color data into two main components of Dim 1 (48.4 %) and Dim 2 (36 %), highlighting key trends and groupings. Different lowercase letters (a, b, c) within the same storage days differ significantly ($P < 0.05$; Duncan's test) among the three treatments. Different lowercase letters (z, y, z) within the same treatment differ significantly ($P < 0.05$; Duncan's test) among the different storage days. Means are presented as SEM (standard error of the mean). LA, Postbiotic of L. *acidophilus* ATCC4356; LGG, Postbiotic of *Lcb. rhamnosus* GG ATCC 53,103.

fillets treated with chitosan or vacuum-packed postbiotics storage for 20-56 days at 4-7°C (Alirezalu et al., 2019; Bungenstock et al., 2020; Tirado-Gallegos et al., 2021). These differences may stem from variations in postbiotic composition, treatment duration, packaging type, or meat matrix. Overall, increased b* values in LA and LGG postbiotics-treated samples suggest improved oxidation stability and color retention, making them promising natural additives for maintaining visual quality in broiler meat during refrigerated storage. In previous studies, it was explained that meat and meat products treated with chitosan, postbiotics, and vacuum packaging help stabilize the color (L*, a*, and b*), by limiting myoglobin oxidation through antioxidant effects and low oxygen permeability (Duran & Kahve, 2020; Hu et al., 2024).

### 3.2.4. Chromatogram (E) value of broiler breast meat

The chromatogram *(E)* value of broiler meat, also known as the total color difference or Euclidean distance, represents the overall visual change in meat color by interpreting lightness (L*), redness (a*), and yellowness values. In the present study, the *E* values range from 4.64-8.09 (Fig. 2D). At day 0, there was no significant difference ($p = 0.271$) observed between the treated and untreated broiler breast meat. However, by day 10, the control meat gradually increased ($p = 0.252$) and had the highest *E* value (6.42), indicating greater discoloration due to oxidative deterioration, spoilage, and freshness (Shimizu & Iwamoto, 2022). In contrast, LA and LGG postbiotics-treated broiler meat samples maintained significantly lower *E* values (4.64 and 4.71, respectively; $p < 0.001$), indicating better color stability of meat. This suggests that postbiotics reduced oxidative or enzymatic degradation of meat pigments, improving broiler meat's aesthetic and perceived color quality. Previous studies also reported that postbiotics inhibit spoilage microorganisms and delay oxidation, supporting these findings (Doski & Yaseen, 2023; Lauková et al., 2024).

### 3.2.5. Chroma (C*) values of broiler breast meat

Chroma (C*) quantifies the intensity or saturation of color and is calculated from the redness (a*) and yellowness (b*) values. Higher chroma indicates a more vivid and appealing color, which is important for consumer perception. In this study, C* values of broiler breast meat ranged from 13.80 to 17.18 (Fig. 2E). At days 0 and 3, differences were not significant ($p = 0.986$ and $p = 0.257$). During storage, broiler meat treated with LA and LGG postbiotics showed higher chroma values after 7 days. By day 10, both postbiotics (17.18 and 16.83, $p < 0.05$) outperformed the control group (13.98), indicating enhanced color saturation and stability. This higher visual quality and freshness of meat may stem from slower oxidation and better preservation of pigments (Seo et al., 2024; Zhang et al., 2018; Zhu et al., 2022). The control meat exhibited a numerical decrease in chroma values 915.08 to 13.98), likely due to metmyoglobin formation and lipid oxidation, correlating with higher TBARS, which are linked to decreased chroma and color stability (Dursun & Güler, 2023).

### 3.2.6. Hue (H*) values of broiler breast meat

Hue angle (h*), which reflects perceived meat color, is calculated using the redness (a*) and yellowness (b*) values, with 0 ° representing red and 90 ° representing yellow. In this study, h* values for broiler breast meat in control increased slightly from 78.11 to 83.02 over 10 days, indicating a shift toward yellowish tones (Fig. 2F). However, in both LA and LGG postbiotics-treated meat, the hue values were significantly lower ($p < 0.05$) throughout the storage, particularly for LGG (80.55 at day 10). This suggests that postbiotic treatments may help preserve a reddish appearance and reduce discoloration in broiler meat, likely due to their antioxidant and antimicrobial properties. Similar results were reported by Iakubchak et al. (2024), where probiotics and their bioactive compounds helped maintain redness by slowing myoglobin oxidation. However, this oxidation results in discoloration, with higher hue values indicating increased yellowness, which could be viewed negatively(Bogatko, 2024; Hu et al., 2024). ANOVA results (Table 5) confirmed that both treatment (control, LA, and LGG) and storage time (0, 3, 7, and 10 days) significantly affected all color coordinates (L*, a*, b*, C*, h*, and E*) of broiler meat, with postbiotics contributing to pigment retention and improved visual quality. These changes may be associated with pH modification and reduced oxidative stress induced by postbiotics compounds. The correlation coefficient of physicochemical parameters and color properties of postbiotic-treated broiler meat is depicted and described in Supplementary Figure S1.

## 3.3. Effect of postbiotics on texture properties of broiler meat

The texture of meat is a key characteristic that affects consumer satisfaction and the overall eating experience. Attributes like tenderness, juiciness, and chewiness significantly influence consumer perceptions. Therefore, understanding these factors is crucial for producers to meet consumer demands. Studies have shown a correlation between sensory and instrumental texture analysis for meat products (Pematilleke et al., 2022). The study investigates the impact of LA and LGG postbiotics on the texture profile of raw and cooked broiler breast over 10 days of chilled storage. Figs. 3 and 4 and Supplementary Tables S5 and S6 illustrate the significant effects of treatment (control, LA, LGG) and storage duration (0, 3, 7, and 10 days) on raw and cooked meat texture. Bar graphs (Fig. 3 A-E and 4 A-E) display these effects, while a heatmap (Figs. 3 F and 4 F) shows the clustering of texture parameters. The PCA biplot (Figs. 3 G and 4 G) condenses the texture data into two main components, revealing key trends and groupings. The primary difference between the texture profile of raw and cooked broiler meat is that raw meat is significantly softer and more pliable. In contrast, cooked meat becomes firmer, more cohesive, and slightly drier due to the denaturation of proteins during cooking (Kim et al., 2025).

### 3.3.1. Hardness value of raw and cooked broiler meat

Meat hardness can be understood as the force needed to achieve the first significant deformation in the meat. It represents the initial resistance felt while chewing with our molars. In this study, both raw and cooked broiler breast meat exhibited significant variations in hardness across treatments during storage. On day 0, no significant differences were observed among control, LA, and LGG groups in raw meat (301.32-309.68 g; $p = 0.205$, Fig. 3A) or cooked meat (1046.42-1209.68 g; $p = 0.228$, Fig. 4A). However, by days 3, 7, and 10, hardness values of raw and cooked meat decreased significantly in all samples ($p < 0.001$), with postbiotics-treated meat (LA and LGG) exhibiting lower hardness than the control, indicating better texture preservation during chilled storage. This reduction in hardness is likely due to the proteolytic activity and moisture loss over time (Barido & Lee, 2021). The present findings align with Masoumi et al. (2022), who stated reduced hardness in raw chicken fillets marinated with regular and probiotic yogurt (*L. casei*) and

**Table 5**
Different treatments (control, LA, and LGG) and storage periods (0, 3, 7, and 10 days) affect broiler breast meat color coordinates.

| ANOVA (P-value) | Lightness (L*) | Redness (a*) | Yellowness (b*) | Chromatogram (E) | Chrome (C*) | Hue (h*) |
|---|---|---|---|---|---|---|
| Main effect | | | | | | |
| Treatment (T) | 0.000 | 0.000 | 0.001 | 0.002 | 0.000 | 0.000 |
| Storage (S) | 0.000 | 0.025 | 0.035 | 0.163 | 0.064 | 0.000 |
| 2-way interactions | | | | | | |
| T X S | 0.000 | 0.000 | 0.011 | 0.000 | 0.012 | 0.000 |

LA, Postbiotic of L. *acidophilus* ATCC4356; LGG, Postbiotic of *Lcb. rhamnosus* GG ATCC 53,103.

stored at 4°C for 6 days. Similarly, Soysal et al. (2015) found that chicken drumsticks treated with various antimicrobial substances and stored for six days exhibited significant changes in hardness. Postbiotics (LA and LGG) treatment appears to mitigate structural deterioration by maintaining protein-water interactions, thereby improving the chewing sensation. On day 0, higher hardness values can be attributed to limited ATP availability, which impairs the relaxation of actomyosin cross-link bridges (Ertbjerg & Puolanne, 2017). Over time, increased proteolysis breaks these cross-links, resulting in reduced hardness by day 10 (Lana & Zolla, 2016). The hardness values of raw and cooked broiler meat vary significantly due to cooking method, cooking temperature, physical and chemical treatments, and woody breast condition (Xing et al., 2020). The characteristics of raw meat influence the hardness of cooked meat, requiring more force to cut, indicating a higher hardness level. Despite overall softening during storage, postbiotic-treated samples (LA and LGG) maintained better textural integrity than the control, highlighting their potential to enhance meat tenderness and storage quality.

### *3.3.2. Cohesiveness value of raw and cooked broiler meat*

Cohesiveness in meat is defined as the ability of meat to retain its structure and adhere together across multiple compression cycles. A higher cohesiveness indicates that the meat maintains its form and resists disintegration. Changes in WHC can significantly affect the cohesiveness of meat, as water loss reduces structural integrity (Mir et al., 2017). Additionally, protein denaturation, particularly in muscle fiber structures like actin and myosin, can decrease the cohesiveness score. The study found no significant differences in cohesiveness among treatment samples during most storage periods, but some trends emerged. In raw broiler meat (Fig. 3B), on day 10, the cohesiveness of the LA postbiotics-treated groups (0.60) was significantly higher ($p > 0.05$) than both the LGG postbiotics-treated group (0.58) and the control group (0.51). As the storage period progressed, cohesiveness in the postbiotics-treated meat tended to increase, while it decreased in the control group, indicating a potential benefit of postbiotics in maintaining meat structure over time. In cooked broiler meat (Fig. 4B), cohesiveness was comparable across treatments, with a similar trend observed. LA postbiotics-treated meat had significantly ($p < 0.05$) higher cohesiveness after 7 (0.84) and 10 (0.85) days compared to the control (0.76) and LGG postbiotics-treated meat (0.81 and 0.83). These results suggest that LA postbiotics improve cohesiveness during storage, contributing to better structural integrity, especially in cooked meat. These findings align with studies by Masoumi et al. (2022), which reported no significant changes in cohesiveness in raw chicken fillets dipped with regular or probiotic yogurt (*L. casei*) over 6 days kept at 4°C. In contrast, the present study highlights the significant improvement in the cohesiveness of broiler meat treated with postbiotics, especially with LA. This may be attributed to enhanced protein-protein interactions and inhibition of spoilage microorganisms, which positively affect meat quality and acceptability during the extended storage period (Chumngoen & Tan, 2015; Isaac-Bamgboye et al., 2024). Cooked broiler meat consistently exhibited higher cohesiveness than raw meat, as shown in Supplementary Table S6. This is due to structural changes such as moisture reduction, protein denaturation, and collagen solubilization during cooking, which enhance texture and mouthfeel (Nasrollahzadeh et al., 2024). Studies by Kim et al. (2025) and Chumngoen and Tan (2015) confirmed that cooking improves cohesiveness, which is essential for texture and sensory qualities. Overall, LA postbiotics significantly enhance the cohesiveness of broiler meat, especially during prolonged storage, improving meat quality and structural integrity.

### *3.3.3. Springiness value of raw and cooked broiler meat*

Springiness refers to a meat's ability to return to its original shape after compression, reflecting its elasticity and resilience during chewing. Higher springiness values indicate better structural recovery, contributing positively to texture and mouthfeel. Factors such as storage duration, biochemical changes, physical, chemical, and biological treatment, and marination influence this property (Tran & Truong, 2024). The breakdown of collagen into gelatin during storage softens the meat structure and may influence springiness by altering connective tissue content (Florek et al., 2022). In the current study, there were no significant ($P < 0.05$) differences in springiness among treatments in raw and cooked broiler meat on day 0 (Fig. 3C and 4C). Throughout the storage period, the control group raw meat showed a significant fluctuation in springiness values, peaking at 1.47 mm on day 7 ($p < 0.001$). In contrast, LA and LGG postbiotics-treated samples maintained relatively stable springiness values. For cooked meat, although all groups initially were similar ($p > 0.05$), a significant reduction in springiness was observed in the control after 7 days ($p < 0.001$). However, LA and LGG postbiotics-treated meat samples maintained higher springiness (1.62-1.78 mm and 1.66-1.80 mm, respectively), with no significant difference between these treatments across all storage days. The preserved elasticity in postbiotics-treated samples may be attributed to the conversion of collagen to gelatin and stabilization of muscle protein, which supports structural integrity (Ozma et al., 2023). These findings are consistent with (Masoumi et al., 2022), reported a significant increase in springiness in the chicken fillets treated with probiotic yogurt compared to the control over the six-day storage period. Furthermore, NaCl marinades enriched with postbiotics may enhance springiness by improving tenderness, flavor, and juiciness through ionic interactions with myofibrillar proteins, thereby enhancing textural properties during storage (Latoch, 2020), which aligns with current findings. Overall, the consistent springiness in LA and LGG postbiotics in broiler meat during chilled storage suggests that postbiotics can effectively preserve elasticity and texture quality, enhancing consumer appeal over time.

### *3.3.4. Gumminess value of raw and cooked broiler meat*

Gumminess (g) is defined as the product of hardness and cohesiveness, which refers to the energy required to disintegrate semi-solid food during chewing. In broiler meat, gumminess is associated with chewability and internal density and is often influenced by moisture content and protein structure. Prolonged storage typically increases moisture loss and denaturation of muscle proteins and collagen, reducing juiciness while increasing gumminess (Florek et al., 2022). In the present study, in raw meat, initially, gumminess was similar across groups ($p = 0.295$), ranging from 152.45 g to 166.02 g. Over time, all treatment groups experienced significant decline ($p < 0.001$), but the reduction was more pronounced in the LGG postbiotics-treated meat, which reduced sharply to 98.15 g by day 3 and 81.85 g by day 10 (Fig. 3D). On days 3 and 7, LGG postbiotics-treated samples exhibited significantly lower gumminess compared to control and LA samples ($p = 0.031$ and p

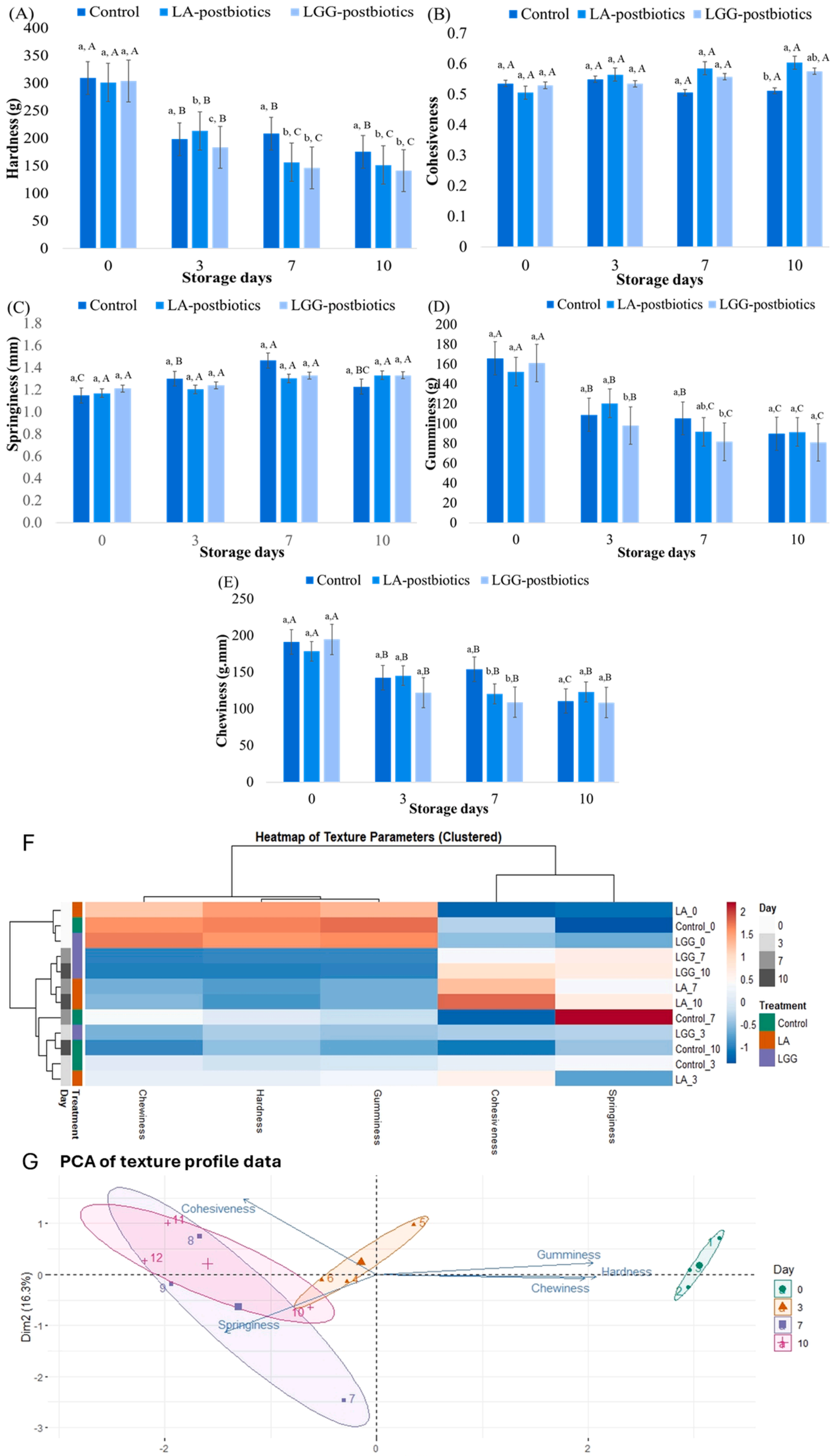


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**Fig. 3.** Effect of treatments (control, LA, LGG) on the texture profile of raw broiler meat samples stored for 0, 3, 7, and 10 days. The bar graphs (A-E) show the temporal changes in individual texture traits: (A) hardness (g), (B) cohesiveness, (C) springiness (mm), (D) gumminess (g), and (E) chewiness (g.mm). Panel (F) shows a cluster heatmap depicting the hierarchical relationship and variation among textural parameters across different treatments and storage days. Panel (G) presents a principal component analysis (PCA) biplot of the texture data, highlighting clustering patterns based on treatments and storage time. PCA reduces multidimensional color data into two main components of Dim 1 (48.4 %) and Dim 2 (36 %), highlighting key trends and groupings. Different lowercase letters (a, b, c) within the same storage days differ significantly ($P < 0.05$; Duncan's test) among the three treatments. Different lowercase letters (z, y, z) within the same treatment differ significantly ($P < 0.05$; Duncan's test) among the different storage days. Means are presented as SEM (standard error of the mean). LA, Postbiotic of L. *acidophilus* ATCC4356; LGG, Postbiotic of *Lcb. rhamnosus* GG ATCC 53,103.

= 0.020, respectively), suggesting enhanced proteolytic activity leading to accelerated structural degradation. By day 10, the differences among groups become nonsignificant (p = 0.147), indicating a convergence of softening effects. In cooked meat (Fig. 4D), no significant difference in gumminess was observed among groups on day 0, with values ranging from 908.18 g to 950.84 g. However, gumminess declined notably in control and LGG postbiotics-treated samples by day 10 (p = 0.013 and p = 0.049, respectively), indicating progressive softening. In contrast, LA postbiotics-treated meat maintained consistently stable gumminess throughout the storage (908.18-898.34 g; p = 0.904), highlighting its protective effect on cooked meat texture (Capan & Bagdatli, 2022). These findings align with (Mia et al., 2024) reported that *L. acidophilus* and its bioactive compounds helped preserve gumminess in cooked meat compared to untreated controls. Similarly, (Masoumi et al., 2022) observed that probiotic yogurt-treated meat samples showed a slower decline in gumminess than regular yogurt or control groups during chilled storage. The relatively stable gumminess in LA postbiotics-treated meat is likely due to improved protein-water binding, influenced by postbiotics components (organic acids, fatty acids, bacteriocins), which help regulate pH and minimize drip loss (Ozma et al., 2022). Overall, LA postbiotics were more effective in preserving gumminess in broiler meat than LGG postbiotics, particularly during prolonged storage, contributing to a firmer and more desirable meat texture.

### *3.3.5. Chewiness value of raw and cooked broiler meat*

Chewiness (g.mm) reflects the energy required to masticate meat until it is ready for swallowing, integrating factors such as hardness, cohesiveness, and springiness (Shikama et al., 2024). While gumminess indicates the force needed to disintegrate food, chewing represents the total effort involved in chewing. In raw broiler meat, chewiness significantly decreased across all treatment groups during storage from 0 to 10 days ($p < 0.01$) (Fig. 3E). By day 7, the chewiness was lower in LA (120.50 g.mm) and LGG (109.11 g.mm) postbiotics-treated meat samples compared to the control (154.15 g.mm) with a significant treatment effect (p = 0.009), indicating a potential tenderizing effect. In cooked broiler meat (Fig. 4E), chewiness did not differ significantly (p = 0.592) between treatments on day 0. Over time, the control group showed a numerical decrease in chewiness by day 10 (p = 0.123). In contrast, the meat samples treated with LA and LGG postbiotics maintained chewiness values that were close to their initial levels. The LA-treated meat samples exhibited slightly higher chewiness on day 10, measuring 1603.93 g.mm, but this difference was not significant compared to the LGG-treated samples. Cooking methods and treatment can influence meat chewiness by altering moisture retention and protein structure (Phumsombat et al., 2025). Stress during slaughter handling can increase energy consumption, lower broiler meat pH, and cause protein denaturation, reduced water-holding capacity, and ultimately decreased chewiness (Ertbjerg & Puolanne, 2017; Sabow et al., 2017). Prolonged storage can cause collagen to break down into gelatin, affecting chewiness. The reduction in chewiness in meat treated with LGG and LA postbiotics suggests enhanced tenderizing, likely improving consumer acceptability. The effect of different treatments (control, LA, and LGG) and storage periods (0, 3, 7, and 10 days) on the texture profile analysis of raw and cooked broiler meat is presented in Tables 6 and 7. In raw meat, treatments significantly affected the hardness and gumminess ($p < 0.001$ and $P < 0.005$), indicating that the control and postbiotics of LA and LGG influenced these properties. No significant main effects were observed for cohesiveness (p = 0.06), springiness (p = 0.611), and chewiness (p = 0.06), summarizing that these properties were not markedly altered by treated and untreated meat. In cooked meat, significant effects were observed on hardness ($p < 0.001$) and cohesiveness (P = 0.032), but not on springiness (p = 0.500), gumminess (p = 0.252), and chewiness (p = 0.944), suggesting that treatments did not markedly alter these properties. Along with the statistically validated results discussed above, these findings are also supported by the HCA clustered heatmap and PCA biplot of raw (Fig. 3F and G) and cooked (Fig. 4F and G), which show that postbiotics can extend shelf life by maintaining desirable texture. Specifically, LGG outperformed LA in delaying texture deterioration, particularly by showing protein degradation, which maintains hardness, and preserving collagen integrity, which retains springiness. PCA biplot also confirmed that storage time is the dominant factor in broiler meat quality, influencing texture changes. Supplementary Figures S2 and S3 provide Spearman's correlation coefficients for texture parameters of raw and cooked broiler meat treated with postbiotics.

## *3.4. The sensory evaluation of broiler breast meat*

With growing consumer demands for high-quality and safe meat products, sensory attributes such as odor, texture, color, and overall acceptability play a crucial role in influencing consumer acceptance and marketability. This study assessed the sensory properties of broiler breast meat marinated with or without postbiotics from LA and LGG during refrigerated storage (4 °C) for 10 days. Changes in sensory scores were evaluated on days 0, 3, 7, and 10 using a 5-point hedonic scale and are presented in Fig. 5 (spider plot) and Supplementary Table S7. On day 0, all samples, including control and postbiotics-treated meat, received the highest scores for all sensory attributes (Fig. 5A), with no significant differences among treatments. As storage progressed, a decline in sensory quality was observed across all groups. However, on day 7, LA and LGG postbiotics-treated samples showed numerically improved odor scores (3.67), compared to the control (2.85), though not statistically significant (p = 0.094) (Fig. 5B). By day 10, the improvement became significant (p = 0.05), with odor scores of 3.45 out of 5.00 for LA and LGG postbiotics-treated meat (Fig. 5C). This suggests a potential reduction in rancidity due to the antimicrobial and antioxidant effects of postbiotics, resulting in more favorable odor characteristics. Texture and firmness scores remained statistically comparable among treatment groups throughout storage ($p > 0.05$), although LA showed a trend of

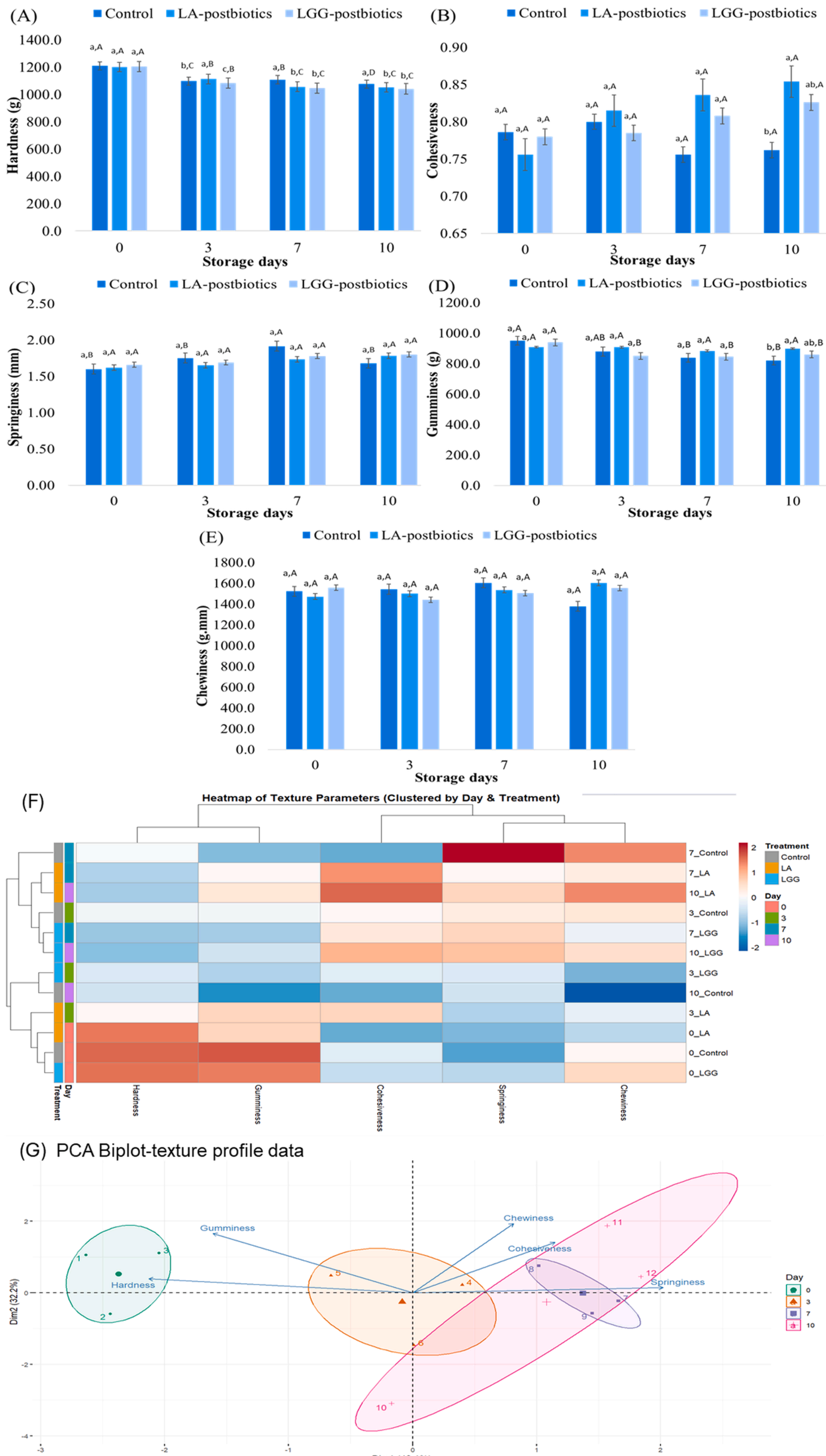


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**Fig. 4.** Effect of treatments (control, LA, LGG) on the texture profile of cooked broiler meat samples stored for 0, 3, 7, and 10 days. The bar graphs (A-E) show the temporal changes in individual texture traits: (A) hardness (g), (B) cohesiveness, (C) springiness (mm), (D) gumminess (g), and (E) chewiness (g.mm). Panel (F) shows a cluster heatmap depicting the hierarchical relationship and variation among textural parameters across different treatments and storage days. Panel (G) presents a principal component analysis (PCA) biplot of the texture data, highlighting clustering patterns based on treatments and storage time. PCA reduces multidimensional color data into two main components of Dim 1 (48.4 %) and Dim 2 (36 %), highlighting key trends and groupings. Different lowercase letters (a, b, c) within the same storage days differ significantly ($P < 0.05$; Duncan's test) among the three treatments. Different lowercase letters (z, y, z) within the same treatment differ significantly ($P < 0.05$; Duncan's test) among the different storage days. Means are presented as SEM (standard error of the mean). LA, Postbiotic of L. *acidophilus* ATCC4356; LGG, Postbiotic of *Lcb. rhamnosus* GG ATCC 53,103.

**Table 6**
The effect of different treatments (control, LA, and LGG) and storage periods (0, 3, 7, and 10 days) on the texture properties of raw broiler breast meat.

| ANOVA (P-value) | Hardness (g) | Cohesiveness | Springiness (mm) | Gumminess (kg) | Chewiness (g.mm) |
|---|---|---|---|---|---|
| Main effect | | | | | |
| Treatment (T) | 0.000 | 0.066 | 0.611 | 0.005 | 0.055 |
| Storage (S) | 0.000 | 0.220 | 0.001 | 0.000 | 0.000 |
| 2-way interactions | | | | | |
| T X S | 0.000 | 0.148 | 0.134 | 0.032 | 0.046 |

LA, Postbiotic of L. *acidophilus* ATCC4356; LGG, Postbiotic of *Lcb. rhamnosus* GG ATCC 53,103.

**Table 7**
The effect of different treatments (control, LA, and LGG) and storage periods (0, 3, 7, and 10 days) on the texture properties of cooked broiler breast meat.

| ANOVA (P-value) | Hardness (g) | Cohesiveness | Springiness (mm) | Gumminess (g) | Chewiness (g.mm) |
|---|---|---|---|---|---|
| Main effect | | | | | |
| Treatment (T) | 0.000 | 0.032 | 0.500 | 0.252 | 0.944 |
| Storage (S) | 0.000 | 0.226 | 0.001 | 0.002 | 0.825 |
| 2-way interactions | | | | | |
| T X S | 0.000 | 0.203 | 0.127 | 0.298 | 0.253 |

LA, Postbiotic of L. *acidophilus* ATCC4356; LGG, Postbiotic of *Lcb. rhamnosus* GG ATCC 53,103.

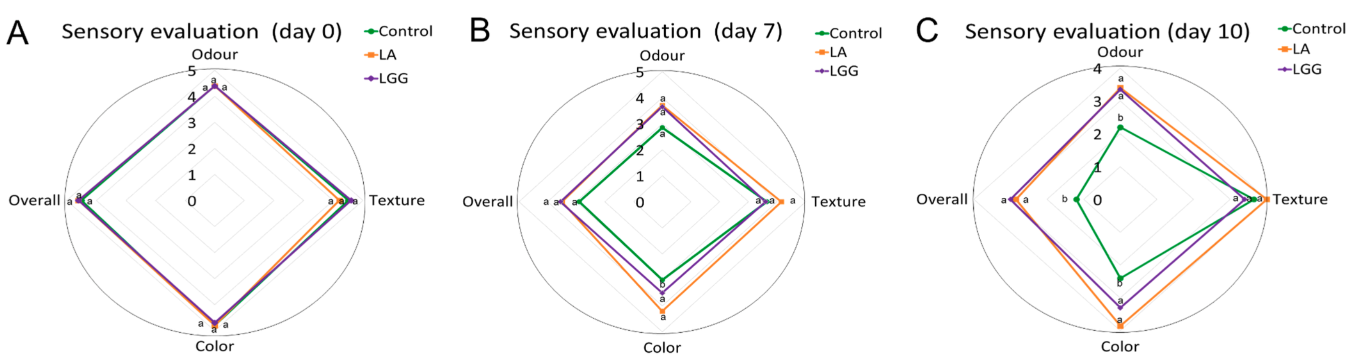


**Fig. 5.** Radar plots displaying the sensory parameters across three treatments of control (green), LA (orange), and LGG (purple), scored by panelists over zero (A), seven (B), and ten (C) days of storage. The lowercase letters denote significant differences among the three treatments within each sensory parameter on a given panel day ($p < 0.05$; Duncan's Test). LA, Postbiotic of L. *acidophilus* ATCC4356; LGG, Postbiotic of *Lcb. rhamnosus* GG ATCC 53,103.

higher firmness (Fig. 5B and C). Notably, LA postbiotics-treated meat samples demonstrated significantly superior color scores on day 7 (4.17) and day 10 (4.00) than the control (3.00 and 2.33, respectively; $p < 0.01$), indicating better visual appeal with golden-brown color. This may be attributed likely due to enhanced retention of meat pigments resulting from postbiotics-mediated microbial inhibition and reduced enzymatic activities or interactions with postbiotics that stabilize the color (Rusman et al., 2024). Similar to the present findings, Chakchouk-Mtibaa et al. (2017), and Mtibaa et al. (2019) demonstrated that the ground turkey meat and beef treated with semi-purified postbiotics (BacFL31 from *E. faecium*) resulted in higher sensory scores compared to the control group stored for 14 days. On day 7, overall acceptability scores of broiler breast meat samples treated with LA and LGG postbiotics were similar to those of the control group ($p = 0.075$), ranging from 2.83 to 3.67. However, by day 10, LA or LGG postbiotics-treated meat samples showed a significant increase in overall acceptability (2.92 and 3.00, respectively), surpassing the control group (1.16, $p = 0.027$), indicating enhanced shelf life and consumer appeal. Consistent with the present findings, Reda et al. (2024) reported that the addition of the probiotics of *Bifidobacterium bifidum and L. rhamnosus* improved the color, odor, consistency, and overall acceptability of ground beef samples and extended the shelf life of the beef during refrigerated storage. Smaoui et al. (2016) found that different concentrations of BacTN635 used alone or with *Mentha piperita* essential oils improved the acceptability of raw minced meat after 7 days of storage compared to the control. Overall, both LA and LGG postbiotics improved the sensory attributes during storage, with LA postbiotics showing the most favorable effects on color and overall sensory quality. These findings suggest that postbiotics, particularly from LA, are promising natural additives for improving shelf life and consumer acceptance of broiler meat.

## 4. Conclusion and recommendations

The growing consumer demand for high-quality, minimally processed broiler meat has led to exploring natural bio-preservatives such as postbiotics. This study demonstrated that postbiotics from *Lactobacillus acidophilus* (LA) and *Lacticaseibacillus rhamnosus* GG (LGG) can significantly enhance the physicochemical quality and sensory properties of vacuum-packaged broiler breast meat during 10 days of refrigeration at 4±1 °C. Compared to control, both LA and LGG postbiotics significantly improved meat quality indicators by reducing lipid oxidation (TBARS value: 0.66-0.69 vs. 0.83 mg MDA/kg), stabilizing pH (6.03-6.04 vs. 6.28), lowering drip loss (2.38-2.46 vs. 3.02%) and cooking losses (29.45-32.65 vs. 35.03%), and enhancing water-holding capacity (71.01-73.09 vs. 59.94%). Additionally, postbiotics helped to maintain color stability, particularly higher redness (a* value: 3.12-3.74 on day 10), which is essential for visual appeal. Texture profile analysis in raw meat revealed lower hardness (141.35-151.80 vs. 195.76 g), chewiness (109.11-120.50 vs. 154.15 g.mm on day 7), higher cohesiveness (up to 0.60), and improved springiness (up to 1.33 mm) compared to the control, indicating better mouthfeel. Sensory evaluation confirmed higher odor and overall acceptability scores (up to 3.67 vs. 2.17 in control), especially for LA-postbiotics-treated meat. While the results show promise, there are limitations: postbiotics were produced in a lab with only two LAB strains using MRS broth, and their antimicrobial and antioxidant properties weren't validated by in vitro assays. Additionally, microbial quality indicators and shelf life were not monitored, and the bioactive compounds responsible for preservation weren't characterized. We recommended that future research should investigate a wider range of postbiotics-producing LAB strains, identify and quantify active compounds, optimize production with relevant substrates, assess spoilage and pathogens during storage, and evaluate safety and shelf life in real industrial conditions. Overall, LA and LGG postbiotics show strong potential as clean-label bio-preservatives to enhance broiler meat quality, meet consumer preference for natural products, and reduce reliance on synthetic additives in the meat industry.

## Statements and declarations

### *Ethics approval*

In this sensory evaluation study, verbal/written consent was obtained from all participants after full disclosure of the study. Participation was voluntary, with the right to withdraw at any time. Ethical approval was not required under national regulations, but international ethical standards were followed. No vulnerable populations were involved. None of the authors has conducted any research on animals for this article.

### *Statements and declarations*

The authors declare that they do not have any competing financial interests or personal relationships that could have influenced the work reported in this paper.

### *Funding*

Not applicable.

### *Availability of data and materials*

This article and its supplementary materials include all the essential data generated and analyzed during this study, including experimental data. The commercial lactic acid bacterial strain of *Lactobacillus* strains tested are from ATCC strains.

## CRediT authorship contribution statement

**Md. Moklesur Rahman:** Writing – original draft, Formal analysis, Data curation. **Awis Qurni Sazili:** Writing – review & editing, Visualization, Supervision, Investigation, Conceptualization. **Siti Aqlima Ahmad:** Writing – review & editing, Visualization, Supervision, Conceptualization. **Khalilah Abdul Khalil:** Writing – review & editing, Visualization, Supervision, Methodology, Conceptualization. **Mohammad Rashedi Ismail-Fitry:** Writing – review & editing, Visualization, Supervision, Investigation, Conceptualization. **Ayesha Shiddika Afsana:** Writing – original draft. **Aminul Islam:** Writing – original draft. **Mahdi Foruzanfard:** Writing – original draft. **Md. Sazedul Karim Sarker:** Writing – review & editing, Project administration, Funding acquisition, Conceptualization.

## Declaration of competing interest

The authors declare that they do not have any competing financial interests or personal relationships that could have influenced the work reported in this paper.

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## Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.afres.2025.101260.

## Data availability

Data will be made available on request.

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