Research Article

# Reutilization of Eggshells as a Sustainable Mineral Supplement to Improve Growth Performance and Feed Efficiency in Broiler Chickens

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**Abstract** | The continuous increase in global broiler chicken production demands the availability of efficient, sustainable, and economical feed mineral sources. Calcium (Ca) is an essential mineral for bone growth, metabolism, and production performance, but the industry's dependence on conventional Ca sources such as limestone presents cost and sustainability challenges. Eggshells, which contain approximately 94–95% calcium carbonate, have the potential to be an alternative source of Ca and a solution for food waste management. This study aimed to evaluate the optimal inclusion level of eggshell meal in broiler diets and its effects on production performance. A total of 100 broiler chickens were used in a completely randomized design, with dietary treatments as follows: F1 (basal diet + 0% eggshell powder), F2 (basal diet + 4% eggshell powder), F3 (basal diet + 8% eggshell powder), and F4 (basal diet + 10% eggshell powder). The parameters measured included body weight gain, feed conversion ratio (FCR), carcass percentage, cooking loss, water-holding capacity, pH, and meat tenderness. The results indicated that supplementation with 8% eggshell powder produced the most favorable outcomes, significantly ($p < 0.05$) improving body weight gain, FCR, carcass percentage, cooking loss, water-holding capacity, pH, and tenderness compared to the control group. In conclusion, the inclusion of eggshell powder at 8% in broiler diets can be recommended as an optimal level to enhance growth performance and meat quality traits.

**Keywords** | Eggshell powder, Dietary calcium, Broiler performance, Meat quality

**Received** | January 14, 2026; **Accepted** | April 21, 2026; **Published** | June 17, 2026
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**Citation** | Susalam MK, Mutiar S, Prima HS, Rusfidra, Maulana F, Fajri F (2026). Reutilization of eggshells as a sustainable mineral supplement to improve growth performance and feed efficiency in broiler chickens. J. Anim. Health Prod. 14(3): 847-856.
**DOI** | https://dx.doi.org/10.17582/journal.jahp/2026/14.3.847.856
**ISSN (Online)** | 2308-2801



## INTRODUCTION

Broiler chicken production continues to increase globally, so broiler chicken farming efforts must be optimised to ensure efficiency and sustainability. The success of poultry farming is greatly influenced by adequate feed nutrition, including a balance of essential minerals (Vlaicu *et al*., 2024). One nutrient that is often overlooked is calcium (Ca), even though this mineral plays a central role in chicken growth and health (David *et al*., 2023). The

fulfilment of appropriate mineral requirements is essential to support rapid growth, feed efficiency, and bone health in modern broilers (Javadi *et al*., 2022).

Calcium is a major mineral that plays a role in bone mineralisation, metabolic pathway regulation, and muscle contraction function (Prima *et al*., 2026). Broiler chickens require a strict Ca balance to achieve optimal performance, as excess Ca can inhibit phosphorus (P) availability and cause reduced growth and feed conversion (Rusfidra *et al*., 2025; Walk *et al*., 2022; Li *et al*., 2020). Recommended Ca requirements indicate that a level of around 0.60% is necessary to maximise early growth, while a level approaching 1.00% is necessary to support Ca metabolism and bone integrity in the 1–21 day phase (Chen *et al*., 2022).

On the other hand, the livestock and food industries produce large amounts of eggshell waste (Maulana *et al*., 2025). Eggshells are composed of 93–97% calcium carbonate, along with minor minerals such as magnesium carbonate and calcium phosphate (Chuakham *et al*., 2025), making them a potential source of Ca. However, this waste is often unused and can cause environmental problems (Singh *et al*., 2021). The use of eggshells as an alternative source of calcium is in line with the principles of the circular economy because it can reduce dependence on commercial sources of calcium such as limestone or phosphate, while also reducing feed costs (Shahroom *et al*., 2023).

Several studies have shown that eggshell flour can replace conventional Ca sources without reducing broiler chicken performance (Lee *et al*., 2025). In fact, eggshell powder processed using Averrhoa bilimbi L. fruit filtrate can produce organic calcium that has the potential to replace feed lime (Pratama *et al*., 2021). Broiler response to eggshell supplementation is influenced by the level of use, processing method, particle size, and Ca–P balance in the ration (Dongare *et al*., 2024). Therefore, further research is needed to determine the optimal level that can increase body weight gain, feed efficiency, and mineral utilisation.

The urgency of this research lies in two main aspects, namely nutrition and productivity. The availability of cheap and efficient alternative sources of calcium is an urgent need in the modern poultry industry, which demands rapid growth and low production costs. From an environmental perspective, the utilisation of eggshell waste has the potential to reduce pollution pressure while supporting the concept of circular agriculture through the conversion of organic waste into value-added feed materials. Thus, research on the utilisation of eggshell waste not only contributes to improving broiler chicken performance but also to the development of sustainable waste management strategies (Rusfidra *et al*., 2025).

The eggshells used in this study were sourced from small-scale hatchery waste and waste from street food vendors such as martabak (a popular street food of Indonesia), fried rice, and egg-based beverage sellers. To date, the utilisation of eggshell waste from informal sources such as these has not been widely discussed in international literature. Based on this description, a research was carried out to determine the optimal level of eggshell flour as a mineral supplement in broiler chicken feed, which not only improves growth performance but also supports the utilisation of local food waste as a sustainable source of minerals.

## MATERIALS AND METHODS

### Materials

This study used 100 Platinum broiler chickens one day old (DOC) with an average initial body weight of 40 g. The chickens were kept in cages divided into 20 experimental units, each measuring 1 x 1 m and equipped with feeders, drinkers and heat lamps.

The feed used consisted of commercial feed obtained from PT. Japfa Comfeed Indonesia under the trade name BR1. The nutritional content of BR1 is shown in Table 1. The nutritional composition of eggshell as a supplement for broiler chickens is shown in Table 2. Total calcium and phosphorus levels (%) and Ca: P ratio of experimental diets after eggshell meal inclusion is show in Table 3.

**Table 1:** The nutritional content of BR1 (basal feed).

| Parameter | Specification |
|---|---|
| Moisture (Water Content) | Max 12% |
| Ash | Max 7% |
| Crude protein | Min 21% |
| Crude fat | Min 5% |
| Crude fiber | Max 5% |
| Calcium (Ca) | 0.6 – 1.1% |
| Phosphorus (P) | Min 0.50% |
| **Total amino acids** | |
| Lysine | Min 1.20% |
| Methionine | Min 0.45% |
| Methionine + Cystine | Min 0.80% |
| Tryptophan | Min 0.19% |
| Threonine | Min 0.75% |

Description: Packaging label BR1 Manufactured by PT. Japfa Comfeed, Indonesia.

**Table 2:** Nutrient composition of eggshells as a supplement for broiler chickens.

| Parameter | Value (%) |
|---|---|
| Calcium | 45 |
| Dry matter | 99 |
| Ash | 92 |
| Moisture | 1 |

**Note:** Data obtained during the experiment.

**Table 3:** Total calcium and phosphorus levels (%) and Ca:P ratio of experimental diets after eggshell meal inclusion.

| Treatment | Eggshell inclusion (%) | Ca from eggshell (%) | Basal Ca (%) | Total Ca (%) | Total P (%) | Ca:P ratio |
|---|---|---|---|---|---|---|
| F1 (0%) | 0.0 | 0.00 | 1.00 | 1.00 | 0.45 | 2.22 : 1 |
| F2 (4%) | 4.0 | 1.80 | 1.00 | 2.80 | 0.45 | 6.22 : 1 |
| F3 (8%) | 8.0 | 3.60 | 1.00 | 4.60 | 0.45 | 10.22 : 1 |
| F4 (10%) | 10.0 | 4.50 | 1.00 | 5.50 | 0.45 | 12.22 : 1 |

**Table 4:** Effect of eggshell supplementation in broiler diets on feed intake, body weight gain, and feed conversion ratio.

| Parameters | Treatment | | | | SEM |
|---|---|---|---|---|---|
| | F1 (0% eggshell) | F2 (4% eggshell) | F3 (8% eggshell) | F4 (10% eggshell) | |
| Feed intake (g/bird/week) | 719.33 ± 7.29$^{a}$ | 715.00 ± 13.36$^{a}$ | 693.01 ± 9.62$^{b}$ | 713.09 ± 7.84$^{ab}$ | 5.67 |
| Body weight gain (g/bird/week) | 374.76 ± 0.96$^{a}$ | 390.00 ± 4.80$^{b}$ | 409.21 ± 6.72$^{c}$ | 406.45 ± 1.98$^{c}$ | 2.47 |
| Feed conversion ratio | 1.92 ± 0.02$^{a}$ | 1.83 ± 0.04$^{b}$ | 1.69 ± 0.02$^{c}$ | 1.75 ± 0.01$^{d}$ | 0.01 |

**Note:** $^{a-d}$ distinct superscripts in the same line signify a highly notable variation ($p < 0.01$). SEM = Standard error of the mean.

### Methods

This study employed an experimental method using a completely randomized design (CRD), consisting of four treatments with five replicates each. The treatments involved the supplementation of broiler diets with varying levels of eggshell powder. The treatment groups were as follows: F1 (0% eggshell powder), F2 (4% eggshell powder), F3 (8% eggshell powder), and F4 (10% eggshell powder).

### Time and place of study

This research was conducted over a period of 35 days at the Experimental Farm and Biology and Chemistry Laboratory of the Department of Agroindustry, Faculty of Mathematics and Natural Sciences, Padang State University, Padang, West Sumatra, Indonesia. All animal experimental procedures were carried out in line with International Animal Ethical Standards.

### Eggshell powder production

Eggshells are obtained from the egg processing industry or households. Eggshells are washed with clean water to remove protein residues and other contaminants. The eggshells are then dried in an oven at 100-105°C for 2-3 hours to obtain dry shells. The dry eggshells are ground using a grinder and sieved using a 60-mesh sieve to obtain eggshell powder for use in chicken feed formulations (Zamri *et al.*, 2025).

### Scanning electron microscope (SEM)

Scanning electron microscopy (SEM, FEI ESEM Quanta 200) and energy-dispersive X-ray spectrometry (EDX, FEI ESEM Quanta 200) were used to determine the morphology and elemental composition of the chicken eggshell respectively. The chicken eggshell was prepared and put in a Scanning Electron Microscope stud using a double-backed cellophane tape. The stub and sample were coated with gold and examined using the scanning electron microscope (Ahaduzzaman *et al.*, 2021).

### Data analysis

All collected data were analyzed using analysis of variance (ANOVA). When significant differences among treatments were detected, Duncan's multiple range test was applied for further comparison at a significance level of $p < 0.05$ and $p < 0.01$ (McHugh, 2011).

## RESULTS AND DISCUSSION

### Growth performance

According to statistical research, adding eggshells to broiler diets had a highly significant impact ($p<0.01$) regarding feed consumption, weight growth, and feed conversion value (Table 4).

Feed intake of broilers supplemented with eggshell ranged from 693.01 to 719.33 g/bird/week. The highest feed intake in this study, based on statistical analysis, was observed in treatment F1 (0% eggshell) at 719.33 g/bird/week and treatment F2 (4% eggshell) at 715.00 g/bird/week, while the lowest intake was recorded in treatment F3 (8% eggshell) at 693.01 g/bird/week and treatment F4 (10% eggshell) at 713.09 g/bird/week. Eggshell supplementation displayed a markedly notable effect ($p < 0.01$) on feed intake, according to statistical analysis (Table 4).

The higher feed intake observed in treatment F1 (0% eggshell, 719.33 g/bird/week) and treatment F2 (4% eggshell, 715.00 g/bird/week) was attributed to a more stable nutrient balance, allowing the birds to consume more feed to support growth. At lower levels (0–4%), eggshell meal did not markedly affect feed palatability or mineral balance, resulting in relatively higher intake. This finding is consistent with reports that broiler feed intake is strongly influenced by feed nutrient composition, the energy–protein balance, and mineral content (Mutter *et al.*, 2026). Both insufficient and excessive calcium supplementation can disrupt nutrient homeostasis, whereas moderate levels

can promote optimal intake.

The lower feed intake in treatment F3 (8% eggshell, 693.01 g/bird/week) and treatment F4 (10% eggshell, 713.09 g/bird/week) was due to excess dietary calcium, which tends to bind phosphorus in the digestive tract, forming insoluble complexes. This reduces phosphorus availability, which is essential for bone growth and energy metabolism, leading to discomfort, decreased appetite, and ultimately reduced feed intake. Excessive calcium impairs phosphorus and other mineral absorption in the gut due to the formation of insoluble Ca–P complexes, reducing nutrient metabolism efficiency and leading to lower intake (David *et al*., 2023). High dietary Ca also increases intestinal alkalinity, which reduces digestive enzyme activity, thereby impairing digestion and lowering feed intake. Reported that excessive Ca can increase buffering capacity in the gastrointestinal tract, negatively affecting enzyme activity and reducing intake (Kim *et al*., 2022). These findings imply that while modest amounts of eggshell meal (4%) may be maintained without significant intake loss, large inclusion levels (8%) in broiler diets likely to limit feed consumption.

Body weight gain of broilers supplemented with eggshell ranged from 374.76 to 409.21 g/bird/week. Treatments F3 (8% eggshell) and F4 (10% eggshell) showed the greatest body weight rise at 409.21 g/bird/week and 406.45 g/bird/week, respectively, whereas treatments F1 (0% eggshell) and F2 (4% eggshell) showed the lowest at 374.76 g/bird/week and 390.00 g/bird/week, respectively. Eggshell supplementation exerted a strongly significant influence ($p < 0.01$) on weight growth, according to statistical analysis (Table 4).

The greater body weight gain in treatment F3 (8% eggshell, 409.21 g/bird/week) and treatment F4 (10% eggshell, 406.45 g/bird/week) can be explained by the role of adequate calcium supplementation in supporting broiler growth. Sufficient calcium is crucial for bone mineralization and muscle contraction, ensuring that dietary energy can be efficiently allocated to tissue growth. A balanced Ca–P ratio enhances protein deposition in muscle and growth efficiency. Supplementation of eggshell meal at approximately 8% provided sufficient calcium without interfering with phosphorus absorption, thus supporting nutrient metabolism efficiency. Who reported that eggshell supplementation significantly increased broiler body weight when included at appropriate levels. These findings confirm that eggshells are a potential calcium source to support broiler growth performance (Marlida *et al*., 2023).

The lowest body weight gain in treatment F1 (0% eggshell, 374.76 g/bird/week) was due to calcium deficiency, which is a critical factor in supporting broiler growth. Calcium deficiency inhibits bone mineralization and energy metabolism, resulting in suboptimal muscle growth (Maulana *et al*., 2025). Calcium deficiency has also been reported to reduce digestive enzyme activity and nutrient absorption, ultimately lowering growth efficiency (Shi *et al*., 2021).

Feed conversion ratio (FCR) of broilers supplemented with eggshell ranged from 1.69 to 1.92. The lowest FCR was observed in treatment F3 (8% eggshell) at 1.69, while the highest was in treatment F1 (0% eggshell) at 1.92. The low FCR in treatment F3 (8% eggshell, 1.69) was due to high body weight gain (409.21 g/bird/week) with relatively moderate feed intake (693.01 g/bird/week). This indicates that the birds were able to utilize nutrients more efficiently, with each gram of feed consumed resulting in greater weight gain. This efficiency is associated with sufficient calcium availability from eggshells to support energy metabolism, protein synthesis, and bone mineralization, thereby allowing more dietary energy to be allocated to growth. Previous studies have also reported that eggshell supplementation at optimal levels improves FCR by enhancing nutrient absorption efficiency and muscle deposition (Ogbuewu *et al*., 2023) Feed intake divided by body weight increase yields the FCR value (Mutter *et al*., 2026).

The high FCR in treatment F1 (0% eggshell, 1.92) was attributed to low body weight gain (374.76 g/bird/week) despite elevated feed consumption (719.33 g/bird/week). This occurred because of the lack of supplemental mineral from eggshells, resulting in calcium deficiency. Calcium deficiency forces birds to consume more feed to achieve the same growth, thereby increasing the FCR value. Furthermore, inadequate calcium has been reported to reduce digestive enzyme activity and nutrient absorption, which ultimately impairs growth efficiency (Ogbuewu *et al*., 2023). These findings reinforce that eggshell supplementation improves broiler FCR, with the optimal level ranging from 8–10%. The use of eggshell meal as a mineral source not only increases body weight but also reduces FCR, making it both economically efficient and environmentally sustainable (Rusfidra *et al*., 2025).

## Carcass characteristics

The addition of eggshell powder as a source of calcium (Ca) and micro minerals in broiler rations has a significant effect on the physical properties of meat, including carcass percentage, cooking loss, water-holding capacity, pH, and tenderness. Eggshells have a high calcium carbonate ($CaCO_3$) content (94–97%), as well as essential minerals such as magnesium and phosphorus, which play an important role in bone and muscle tissue metabolism. Observation data on the physical characteristics of meat upon eggshell flour supplementation in broiler chickens can be seen in Table 5.

**Table 5:** Average physical properties of broiler meat with eggshell powder supplementation.

| Parameters Measured | Treatments | | | |
|---|---|---|---|---|
| | F1 | F2 | F3 | F4 |
| Carcass percentage (%) | 73.89 ±5.73[b] | 74.58±2.59[b] | 83.52±2.54[a] | 76.14±3.20[b] |
| Cooking loss (%) | 31.94±0.41[a] | 31.87±0.60[a] | 30.48±0.83[b] | 31.01±0.50[ab] |
| Water holding capacity (%) | 31.18±1.08[c] | 33.88±1.49[b] | 39.63±1.28[a] | 38.16±0.91[a] |
| pH | 6.03±0.11[a] | 5.85±0.06[b] | 5.78±0.05[b] | 5.71±0.11[b] |
| Tenderness (gr $cm^{-2}$) | 5.78±0.09[a] | 5.72±0.13[a] | 4.92±0.69[b] | 5.45±0.16[ab] |

[a-c] distinct superscripts in the same line signify a highly notable variation ($p < 0.05$).

## Carcass percentage

The results of the observation showed that the average carcass percentage showed a significant difference ($p < 0.05$). Treatment F3, which used 8% eggshell powder in the feed, produced the highest value of 83.52 ± 2.54%, which was significantly different from F1, F2, and F4, which ranged from 73.89 to 76.14% (Table 5). This indicates that variations in the Ca level of eggshell flour significantly affect body tissue deposition. The standard deviation in F2 was smaller than in F1, possibly due to lower inter-individual variability, resulting in a more stable and consistent response of broiler chickens to the administration of 8% eggshell powder. The large SD variation in F1 (±5.73) indicated less uniform performance due to commercial feed without extra Ca supplementation.

Treatment F3, which involved administering 8% eggshell powder, produced the highest carcass percentage and was significantly different from the other treatments, Ca supplementation can improve energy and nitrogen metabolism efficiency, resulting in more optimal tissue growth (Chen *et al*., 2022) stated that increased Ca adequacy increases carcass weight and meat weight because it supports skeletal and muscle tissue growth.

The results of this study indicate that the use of eggshell powder at a level of 8% is optimal, whereas 10% in treatment F4 showed no increase in carcass weight. This is possible because excess Ca interferes with phosphorus absorption, has an antagonistic effect on Zn and Mg, and reduces digestive enzyme efficiency. This is consistent with the statements by David *et al*. (2023) that excess Ca can reduce the absorption of other minerals important for growth and can cause antinutritional effects on other minerals in broiler feed.

## Cooking loss (%)

Statistical analysis showed a significant effect ($p < 0.05$) on cooking loss. The lowest value was obtained in F3 (30.48±0.83%), which was significantly different from F1 and F2. The relatively small SD in all treatments (0.41–0.83) indicates that the cooking loss parameter is consistent between samples (Table 5). Low cooking loss values indicate that intramuscular water is better retained during heating. These results are in line with the earlier finding (Evanuarin *et al*., 2023) that the addition of 0.7% eggshell nanopowder to beef patties reduces cooking loss and increases WHC. In F4, the cooking loss value increased again to 31.01%, indicating that excessive Ca supplementation is not therapeutic and can disrupt the ionic balance of muscle tissue.

The lowest cooking loss was found in treatment F3 at 30.48%, indicating that the addition of 8% eggshell improved the meat's ability to retain water during cooking. Cooking loss is strongly influenced by the stability of the myofibrillar protein structure and the intercellular spaces where water is retained (Le *et al*., 2018). It has been reported that $Ca^{2+}$ ions play an important role in heat-induced protein gelation by strengthening the gel network, thereby enhancing the water-holding capacity of myofibrillar proteins such as myosin and casein. This is also in line with (Evanuarin *et al*., 2023) who reported that eggshell nanopowder increases meat structure stability and reduces drying during heating. The addition of eggshell powder at the F3 level of 10% is slightly higher than F2. This indicates that too much Ca can disrupt osmotic balance, causing the release of free water. Thus, the addition of 8% eggshell powder is the effective point for minimising cooking loss.

## Water retention capacity (%)

Water Holding Capacity (WHC) showed significantly different results ($p < 0.05$) with increasing use of eggshell powder. Treatment F3 with eggshell powder showed the highest value of 39.63 ± 1.28%, a sharp increase from F1 (31.18 ± 1.08%; Table 5). This is possible because $Ca^{2+}$ acts as an activator of proteolytic enzymes, which break down post-mortem muscle structural proteins, thereby increasing intercellular space and the ability of proteins to bind water. According to previous research (Chang, 2023) the addition of Ca increases the flexibility of myofibrillar tissue and increases WHC, and Ca plays a role in strengthening electrostatic protein bonds during meat cooling. In treatment F4, the use of eggshell powder at a concentration of 10% showed a slightly lower value than F3, indicating

that there is a saturation point where excess Ca no longer supports protein structure, thereby increasing water-holding capacity on the myofibril surface. Differences in the concentration of eggshell powder used show that WHC is highly sensitive to Ca balance in broiler meat. The highest treatment (F4) slightly reduced the WHC value compared to F3 due to the potential interference of other mineral absorption (Mg, P), which can inhibit the contractile function of muscle fibres in broiler meat.

## Meat pH

Statistical analysis of pH values revealed significant differences ($p < 0.05$) among treatments. A decline in pH was observed post-mortem, reflecting normal glycolytic activity in muscle tissues. The results suggest that calcium supplementation may enhance glycolysis efficiency, contributing to a more pronounced pH decline. Additionally, the low standard deviation values (0.05–0.11) indicate that pH measurements were relatively uniform across samples, demonstrating good consistency within the experimental groups. The ideal pH for broiler meat is in the range of 5.7–6.0, indicating that all treatments are within safe conditions. The decrease in pH is likely due to increased muscle glycogen reserves and improved energy metabolism prior to slaughter. According to (Wang *et al*., 2021) Ca supplementation improves muscle physiological status and facilitates post-mortem lactic acid formation.

The results showed that treatment F3, which used 8% eggshell powder, was the most effective (Table 5). This was because the pH of the broiler meat produced was 5.78 and supported by the highest WHC. In treatment F4, the addition of 10% eggshell powder resulted in a further decrease in pH but was not accompanied by an improvement in meat quality. This was influenced by the higher use of eggshell powder, which affected glycolysis but did not improve muscle structure. The pH of the meat decreased as the level of eggshell powder increased. This decrease in pH was due to an increase in muscle glycogen reserves before slaughter and the smoothness of the post-mortem glycolysis process. According to (Li *et al*., 2020) high Ca bioavailability can improve metabolic health and reduce oxidative stress in broilers, thereby maintaining muscle glycogen. pH values in the range of 5.8–5.7 are still within the ideal range for good quality broiler meat. Lower pH is indicated by brighter meat colour, increased WHC, stable protein structure and microbiological conditions that are still within the threshold.

## Tenderness

The results of broiler chicken meat tenderness testing showed significant differences ($p < 0.05$) among treatments. The F3 treatment exhibited the lowest tenderness value ($4.92 \pm 0.69$ g/cm$^2$), indicating comparatively more tender meat than the other groups (Table 5). The results showed that the lower the meat tenderness, the more tender the meat. The analysis also showed that tenderness tended to vary between individuals but remained statistically significant. This was possible because the eggshell powder containing Ca acted as a calpain activator. This is consistent with the statement by Chen *et al*. (2022) that Ca accelerates the degradation of structural proteins such as titin and desmin. Increased calpain activity results in shorter muscle fibres and a softer texture.

Treatment F4 showed that it was no more tender than F3. Although a higher amount of eggshell powder was administered, this indicated that calpain activity had an optimum point, and it appeared that excess Ca in the use of eggshell powder could cause protein denaturation, which did not lead to an increase in broiler meat tenderness. The best meat tenderness was obtained in treatment F3, which was 4.92 g/cm$^2$. The increase in meat tenderness in line with the addition of eggshell powder is the main activator of the calpain system, an enzyme involved in the controlled degradation of structural proteins such as desmin, titin, and troponin. Calpain activity increases myofibril fragmentation, making the meat more tender (Vlaicu *et al*., 2024). The decrease in tenderness in F4 indicates that excess Ca can cause rapid protein denaturation and disrupt ionic balance in muscle tissue. The combination of high WHC, low cooking loss, and optimal tenderness in treatment F3 with the use of 8% eggshell powder in broiler feed is the optimum.

## Relationship between carcass percentage, cooking loss, WHC, pH and tenderness

The results showed that adding eggshell powder to the feed had a significant effect ($p<0.05$) on all physical parameters of broiler meat, including carcass percentage, cooking loss, water-holding capacity, pH, and tenderness. The relationship between these parameters showed a consistent pattern. This is in line with the physiological, biochemical, and structural mechanisms influenced by the increased availability of calcium (Ca) minerals from eggshell powder. This study shows an increase in carcass percentage, which is related to optimal muscle tissue growth due to the role of Ca with the use of eggshell powder in muscle contraction, enzymatic activity, and cellular energy homeostasis. According to earlier reports (David *et al*., 2023) $Ca^{2+}$ ions act as second messengers in muscle cell proliferation and differentiation, thereby increasing muscle protein deposition and resulting in higher carcass weight. Additionally, other reports (Le *et al*., 2018). State that higher Ca availability is associated with reduced cooking loss and increased water-binding capacity. Biochemically, $Ca^{2+}$ enhances protein gel formation and stabilisation during heating by strengthening inter-filament myofibril bonds. Ca activates the interaction between actin and

myosin and increases intramyofibrillar water retention, enabling the meat to retain more water during the cooking process. This explains the mechanism by which increased Ca in the diet can produce higher WHC values and lower cooking loss.

The pH value of broiler meat also increases with increased administration of eggshell powder, which can maintain the stability of muscle cell membranes and slow down postmortem pH decline. According to (Evanuarin *et al*., 2023) pH stability affects the looseness of myofibril filaments, allowing more water to be physically bound within the protein structure. This affects the tenderness of broiler meat (Chang, 2023) states that high Ca levels can increase the activity of proteolytic enzymes such as calpain, which can accelerate the degradation of myofibril structure after cutting, making the meat more tender due to disruption of the muscle structure.

Overall, the relationship between parameters shows that an increase in the amount of Ca from eggshell powder influences each other through interdependent mechanisms. The amount of Ca affects muscle cell function in myofibrillar proteins, water retention, and structural stability of tissues. This has an impact on improving the physical properties of meat, ranging from higher carcass percentage, lower cooking shrinkage, better water-binding capacity, more stable pH, to softer meat texture. The results of this study indicate that eggshell powder can be used as an effective natural source of Ca to improve the physical quality of broiler meat. According to (David *et al*., 2023) supplementation with organic and inorganic Ca can improve growth performance, muscle tissue formation, and feed conversion efficiency in poultry. Optimal muscle growth results in more mature muscle fibre structure, sufficient glycogen reserves, and stable mineral balance, thereby influencing other meat quality parameters such as pH, water-holding capacity, and cooking shrinkage.

## Scanning electron microscopy (SEM) and energy dispersion X-ray (EDX) analyses

The morphology of the chicken eggshell, as shown in Figure 1, revealed clusters of rough, irregularly arranged, and spongy particles aggregated together, with micropores

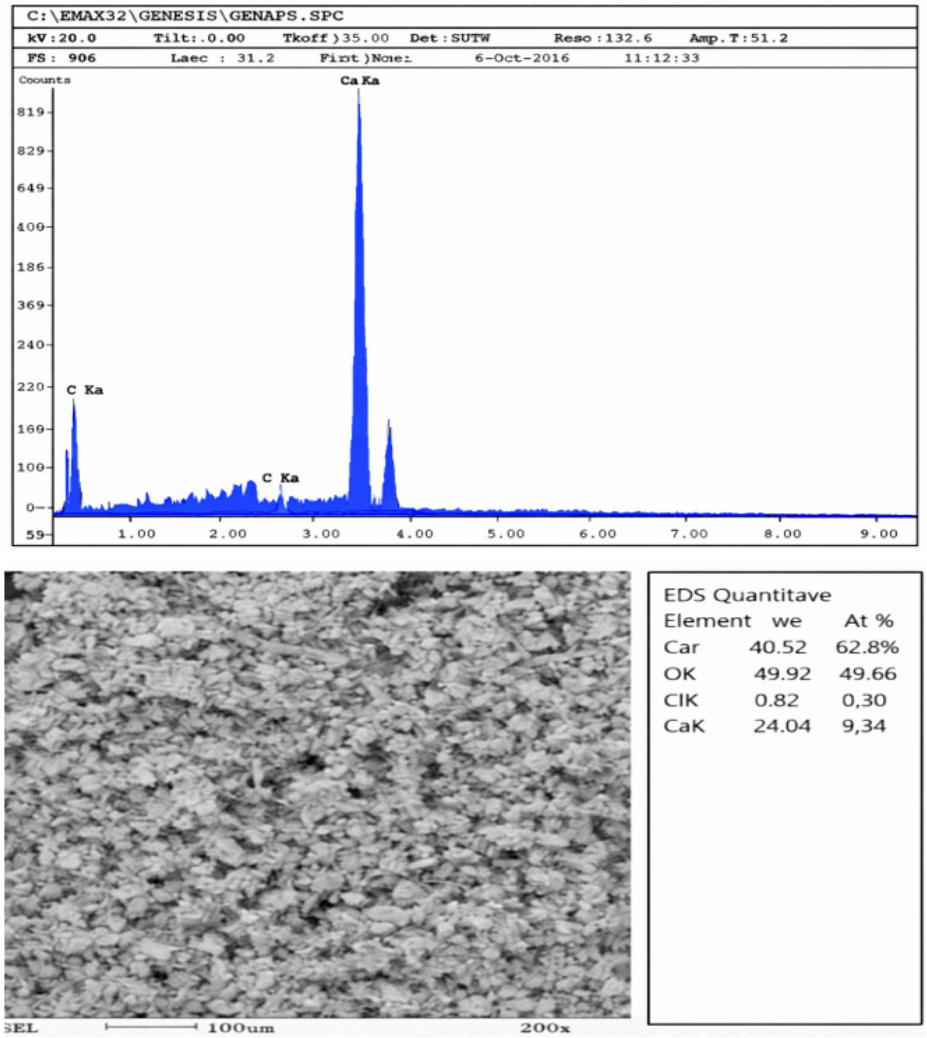


**Figure 1:** Surface morphology and the EDX of chicken eggshell.

distributed across the surface. The small particle size and aggregated structure provide a relatively high specific surface area, which is beneficial for improving mineral solubility and bioavailability when used as a dietary supplement. An increased surface area enhances the interaction between digestive enzymes and mineral particles, thereby facilitating calcium release and absorption in the gastrointestinal tract of broiler chickens. Thermal processing or calcination of eggshells has been reported to further enhance microporosity and surface area, potentially improving mineral availability (Abd Mutalib *et al*., 2017; Viriya *et al*., 2012).

Elemental composition analysis using EDX (Figure 1) confirmed that the eggshell primarily consisted of calcium-rich compounds, with carbon (62.80%), oxygen (49.92%), chlorine (0.30%), and calcium (9.34%) detected. The dominance of calcium indicates that eggshells can serve as an effective and sustainable calcium source in broiler diets, supporting skeletal development, growth performance, and feed efficiency. The presence of carbon in the eggshell matrix may also contribute to improved structural characteristics and mineral dispersion, which can enhance nutrient utilization in the digestive system. Overall, the mineral-rich composition and porous microstructure of chicken eggshells support their potential reutilization as a sustainable mineral supplement to improve growth performance and feed efficiency in broiler chickens (Zampiga *et al*., 2021).

## CONCLUSIONS AND RECOMMENDATIONS

The results of this study indicate that eggshell powder can be used as an effective natural source of calcium to improve the physical quality of broiler meat. Adding 8% eggshell powder to the broiler diet is the optimal combination that affects meat quality and can increase carcass percentage, increase WHC, reduce cooking loss, and improve tenderness. Eggshell powder has the potential to be a sustainable source of minerals to improve broiler performance and support the concept of circular economy in the poultry industry.

## ACKNOWLEDGMENTS

The authors would like to express their deepest gratitude to Universitas Negeri Padang for the financial support provided through the Beginner Research Grant Scheme (Penelitian pemula) under Grant Contract No. 1953/UN35.15/LT/2025. This support was invaluable in facilitating the entire research process-from experimental design and implementation to the preparation of this scientific manuscript.

The authors also extend their sincere appreciation to all members of the Faculty of Animal Science and the Institute for Research and Community Service (LPPM) at Universitas Negeri Padang for their facilities, guidance, and technical assistance throughout the course of this study.

## NOVELTY STATEMENT

This study presents a novel approach by reutilizing eggshell waste as a sustainable mineral supplement for broiler chickens, thereby addressing both nutritional needs and environmental concerns. It uniquely integrates nutritional evaluation, feed efficiency, and environmental sustainability within a single experimental design to comprehensively assess broiler performance as well as carcass percentage. Furthermore, the research strengthens the principles of waste-to-feed conversion and supports the concept of a circular economy in modern poultry production systems, promoting resource efficiency and reducing environmental waste.

## AUTHOR'S CONTRIBUTION

Malikil Kudus Susalam designed the overall research framework, supervised the experimental implementation, and performed the scientific revision of the manuscript. Muchlisinalahuddin was responsible for feed formulation, management of experimental activities, and statistical data collection. Heppy Setya Prima conducted sample preparation, laboratory analysis, and interpretation of the research findings. Sri Mutiar participated in field research activities and monitored broiler growth throughout the experimental period. Rusfidra assisted in data processing, preparation of tables and figures, and the initial drafting of the manuscript. Fajri Maulana contributed to the development of the discussion section, scientific review, and refinement of the manuscript content. Fadhli Fajri was involved in literature review, final editing, and overall manuscript alignment.

### Generative AI and AI assisted technology statement

The authors declare that no generative AI and AI assisted technology was used in the creation of this manuscript.

### Conflict of interest

The authors have declared no conflict of interest.

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