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FROM WASTE TO FEED: A REVIEW OF RECENT KNOWLEDGE ON INFERTILE EGG AS A PROTEIN-RICH FEEDSTUFF FOR BROILER CHICKENS

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Abstract: Infertile egg is a by-product of the poultry hatchery with great potential as an alternative protein source for broiler chickens. This review provides an update on the nutritional value, processing methods, and beneficial effects of using infertile egg meal in broiler diets. Infertile eggs are comparable in nutritional value to fertile and table eggs, with high levels of protein, essential fatty acids, vitamins, and minerals. Processing methods such as spray-drying, oven-drying, and freeze-drying can convert infertile eggs into a powdered form suitable for broiler feed formulation. Studies have shown that including infertile egg meal can improve growth performance, nutrient digestibility, intestinal health, antioxidant status, and meat quality in broilers without negatively impacting production costs. However, challenges such as variations in nutritional composition due to processing methods and potential microbial contamination during the hatching process need to be addressed. Future research should focus on optimising inclusion levels, processing methods, and environmental impact assessments to advance the sustainable use of this valuable protein source in broiler nutrition.

Key words: *alternative feed, poultry, hatchery by-product, soybean meal, sustainability*

INTRODUCTION

Feed is a crucial factor in broiler chicken production. Maize, a source of energy, and soybean meal, a source of protein, are the primary ingredients in broiler rations, and their prices are currently highly fluctuating due to climate change and uncertain geopolitical conditions. Among the feed ingredients in broiler rations, protein sources have the highest prices, hence significantly impacting overall production costs. To ensure the sustainability of broiler production, farmers are seeking alternative protein sources. One such ingredient is infertile egg, a by-product of poultry hatcheries.

The broiler chicken industry is currently growing, and a consequence of this development is the increasing production of infertile eggs by poultry hatcheries (Islam et al., 2017; Suprayogi et al., 2025a). As waste, infertile eggs are not permitted for human consumption according to Commission Regulation (EC) No. 617/2008

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(Commission Regulation, 2008), so they have no economic value. Nutritionally, there is no difference in nutritional value between infertile eggs, fertile eggs, and table eggs (Ratriyanto et al., 2021). Therefore, infertile eggs have great potential as an alternative, low-cost protein source for broiler chickens. As a high-protein ingredient, the use of infertile eggs as a feedstuff can potentially reduce broiler farmers' dependence on soybean meal. Furthermore, the use of infertile eggs as a feed ingredient can have a positive impact on the environment, especially by reducing greenhouse gas (GHG) emissions and unpleasant odors (Dallaire-Lamontagne et al., 2024). Despite its potential as an alternative protein source for broiler chickens, the use of infertile eggs as a feed ingredient faces several challenges. The heterogeneity of infertile eggs' nutritional value due to differences in processing methods and the potential for contamination by pathogenic microbes in the hatchery (Esmailzadeh et al., 2013; Suprayogi et al., 2025a) is challenge that must be addressed. Standardizing processing methods and freeing infertile eggs from potential contamination by harmful microbes will provide certainty and safety in broiler chicken ration formulations.

Currently, there is no comprehensive review of the use of infertile eggs as a feed ingredient for broiler chickens in the literature. This review provides update knowledge on infertile eggs as a protein-rich feedstuff for broiler chickens.

METHODOLOGY OF REVIEW

In the preparation of this review article, the authors conducted a comprehensive literature search focusing on recent advancements in the utilization of infertile eggs as a protein-rich feedstuff for broiler chickens. In light of the limited research on infertile eggs as a protein source for broiler chickens, a literature search was performed. This search targeted articles from the last 20 years (2006 to 2026) to compile a more comprehensive collection of relevant studies. Peer-reviewed journal articles in English were selectively collected and analyzed to substantiate the data. In addition to that, a selective examination of conference proceedings indexed by internationally recognized indexing services was also conducted. Studies concerning the utilization of hatchery waste, excluding infertile eggs, and the application of infertile egg meal for purposes other than broiler chicken production were not incorporated into the article review. The keywords employed during the literature search included "broiler chicken", "hatchery byproduct", "protein-rich feed", and "infertile egg". To gather pertinent articles, several scientific databases were employed, including Elsevier ScienceDirect, ProQuest Research Library, and Wiley Online Library. Additionally, Google Scholar was used as an alternative when the needed articles were unavailable through the previously mentioned scientific platforms. In the course of the literature search, 68 articles were initially collected. Following a comprehensive review, only 36 articles were deemed suitable for inclusion in this article review. All the studies cited were evaluated for their scientific rigor, which included examining the use of proper controls, statistical analyses, and clarity in reporting. Nonetheless, due to the narrative format of this review, no formal quality assessment tools were utilized.

INFERTILE EGG AS A POULTRY HATCHERY BYPRODUCT

Infertile eggs are those not fertilized by a rooster, and consequently, they do not undergo embryonic development during the hatching process (Islam et al., 2017). While fertile eggs contain a blastoderm, a single layer of embryonic epithelial tissue forming the blastula, infertile eggs possess a germinal disc, also known as a blastodisc (Adegbenjo et al., 2020). Fertile eggs can be identified by the presence of blood, which signifies embryonic development after a period of incubation. Typically, after 96 hours of incubation, blood becomes visible in a fertile egg, whereas it remains absent in an infertile one (Islam et al., 2017). Infertile eggs in poultry hatcheries pose a significant economic challenge. According to poultry hatchery statistics, about 5-20% of all eggs placed in an incubator are infertile (Islam et al., 2017; Suprayogi et al., 2025a). In the poultry industry, a method called candling is usually used to take out infertile eggs from the incubator. This is usually done between 7 to 10 days of incubation to check if the eggs are fertile. Since this method takes a lot of time, only a few eggs are checked. Most infertile eggs are not removed and stay in the incubator until day 18 (Islam et al., 2017). Since incubating infertile eggs can occupy valuable space and consume energy, it reduces the efficiency and causes economic losses for poultry hatcheries. Often, a substantial percentage of infertile eggs are incubated alongside fertile ones. Over time, this practice can lead to contamination of the entire batch because some infertile eggs become 'exploder eggs' due to bacterial contamination inside the egg, causing gas buildup and leading the egg to explode (Adegbenjo et al., 2020). Considering all these factors, the ability to identify infertile eggs before incubation would significantly increase hatching rates, lower costs, and conserve incubator space.

Eggs placed in an incubator are deemed unsuitable for human consumption. According to European Union Commission Regulation (EC) No. 617/2008 (Commission Regulation, 2008), such eggs, regardless of the duration they spend in the incubator, are prohibited from being used for human consumption or as raw materials in the food industry. Consequently, infertile eggs are regarded as waste with no economic value. Improper management and handling of these infertile eggs can lead to negative environmental impacts, including the emission of GHG and unpleasant odors (Dallaire-Lamontagne et al., 2024). Infertile eggs are rich in organic materials, particularly protein and fat, which create favorable conditions for pathogen development (Lopes et al., 2024; Suprayogi et al., 2025ab). The degradation of amino acids in these eggs results in an increase in pH and the release of ammonia, sulfides, and amides, all of which are associated with rotting odors (Dallaire-Lamontagne et al., 2024). Regarding GHG production, emissions are not directly produced by the infertile eggs during storage but rather arise from the methods used to manage and process them as part of hatchery residue. One such method is conventional rendering, which involves heat treatment of the infertile eggs and is linked to high levels of GHG emissions, as well as significant energy consumption. Another method is composting, which, although considered a low-cost alternative, also generates GHG. During the storage and spreading of composted residues, gases such as ammonia, methane, and nitrous oxide are released. Special attention should be given to infertile eggs due to their high protein content, which can impair the composting process, extend its duration, and increase GHG emissions due to nitrogen volatilization if not properly managed with carbon-rich additives (Dallaire-Lamontagne et al., 2024).

Infertile eggs have not been extensively utilized up to this point (Suprayogi et al., 2025a, b). Due to their substantial protein and fat content, these eggs can be employed in the production of pet food or transformed into a dried and ground powder to be added to the feed of animals such as broiler chickens and pigs. Once the eggshell is removed, infertile eggs can be converted into egg meal through a specific processing method (Lopes et al., 2024).

NUTRITIONAL CONTENTS OF INFERTILE EGG

Eggs are esteemed for their nutritional importance, acting as a crucial source of both macronutrients and micronutrients. They are distinguished by their high-quality protein content, essential fatty acids, and a wide array of vitamins and minerals. A key nutritional element of eggs is their protein, which is of exceptional quality and contains all the essential amino acids. Beyond protein, eggs also offer essential fats (Miranda et al., 2015). Additionally, eggs are rich in vitamins such as vitamin D, B vitamins (including B12 and riboflavin), and folate, as well as minerals like selenium, iodine, and phosphorus (Myers & Ruxton, 2023). The nutritional composition of infertile eggs is comparable to that of fertile eggs and table eggs, with no scientific evidence suggesting a difference in their fundamental nutritional values. Some research has documented the nutritional profiles of infertile egg meal (Table 1), which comparable to that of many conventional feed ingredients for livestock, such as soybean meal (Ratriyanto et al., 2020).

There are variations in the nutritional values of infertile egg meal reported by several researchers. For example, Suprayogi et al. (2025a) reported a crude protein content of 31.47% in infertile egg meal, lower than the 43.5% reported by Esmailzadeh et al. (2013). This difference arises from differences in the production (processing) of infertile egg meal. Esmailzadeh et al. (2013) mixed egg white and egg yolk, which were then spray-dried at a temperature of 55 °C, without adding other ingredients. In preparing infertile egg meal, Suprayogi et al. (2025a,b) added 10% wheat flour (w/w) and 10% palm oil (w/w) to the egg white and egg yolk mixture before oven-drying at 70 ºC. The addition of other materials during the production process resulted in a lower percentage of crude protein in the infertile egg meal product. Meanwhile, Akinola et al. (2020) did not add any other ingredients to the infertile eggs

Table 1.
Nutritional contents of infertile egg meal reported by some studies

Items	Values	References
Nutrient contents		
Crude protein, %	31.5 – 50.4	Esmailzadeh et al., 2013; Akinola et al., 2020; Choi et al., 2021; Akhirini et al., 2021; Haruni et al., 2025; Suprayogi et al., 2025b
Crude fat, %	26.9 – 38.7	Esmailzadeh et al., 2013; Akinola et al., 2020; Akhirini et al., 2021; Haruni et al., 2025; Suprayogi et al., 2025b
Crude ash, %	1.99 – 27.6	Akinola et al., 2020; Choi et al., 2021; Haruni et al., 2025; Suprayogi et al., 2025b
Crude fiber, %	0.59 – 2.39	Akinola et al., 2020; Akhirini et al., 2021; Haruni et al., 2025; Suprayogi et al., 2025b
Calcium, %	0.05 – 8.90	Esmailzadeh et al., 2013; Akinola et al., 2020; Choi et al., 2021; Akhirini et al., 2021; Suprayogi et al., 2025b
Phosphorus, %	0.18 – 7.50	Esmailzadeh et al., 2013; Choi et al., 2021; Akhirini et al., 2021; Suprayogi et al., 2025b
Metabolizable energy, kcal/kg	3,950.0 – 5,668.0	Esmailzadeh et al., 2013; Akinola et al., 2020; Choi et al., 2021; Akhirini et al., 2021; Haruni et al., 2025; Suprayogi et al., 2025b
Amino acids, %		
Lysine	2.30 – 6.99	Esmailzadeh et al., 2013; Choi et al., 2021
Methionine	3.29	Esmailzadeh et al., 2013
Methionine+cysteine	1.80 – 5.70	Esmailzadeh et al., 2013; Choi et al., 2021
Threonine	1.80 – 4.65	Esmailzadeh et al., 2013; Choi et al., 2021
Tryptophan	0.40	Choi et al., 2021

before oven-drying at 75 ºC. They reported a crude protein content of 50.4% in the infertile egg meal product.

Fermentation is one of the simple processes that can be used to improve the nutritional value of eggs. Studies show that fermentation using lactic acid bacteria, in addition to increasing nutritional contents, can also improve the sensory quality and functional properties of eggs, such as increasing antioxidant capacity and reducing cholesterol in eggs (Shang et al., 2025). Consistent with the aforementioned study, fermentation of infertile egg meal using *Saccharomyces cerevisiae* increased crude protein content. Fermentation also increased selenium content in infertile egg meal, thus providing functional benefits to the health and antioxidant status of broiler chickens (Anggraeni et al., 2025). However, to date, the fermentation of infertile egg meal and its application on broiler chickens is still limited.

POTENTIAL OF INFERTILE EGG AS AN ALTERNATIVE PROTEIN SOURCE IN BROILER FEEDS

In addition to having a higher protein content, animal-based proteins typically have higher digestibility and greater essential amino acids compared to plant-based proteins. In such respect, animal-based proteins are considered to have a higher nutritional value than most plant-based proteins primarily due to their superior anabolic properties, which means they are more effective at stimulating muscle protein synthesis (Berrazaga et al., 2019). Currently, fish meal and meat-bone meal are the most popular animal-based proteins used for broiler chicken diets. Their high content of crude protein and amino acids is an advantage as animal-based protein sources for broiler chickens. However, due to the high price of fish meal, its use in broiler chicken feed can increase broiler production costs (Frempong et al., 2019). Meat-bone meal is actually cheaper than fish meal and is very profitable as an animal-based protein in broiler chicken feed. However, the use of meat and bone meal is often hampered by the varying nutritional content of meat and bone meal (depending on the raw meat and bone materials used to produce it), making it difficult for poultry nutritionists to formulate rations for broiler chickens (Eagleson et al., 2018).

In a previous study, Choi et al. (2021) compared the crude protein content of infertile egg meal and fish meal. The crude protein content of infertile eggs is significantly lower than that of fish meal, with fish meal containing 68.5% crude protein, while infertile eggs contain 34.2%. With particular regard to the amino acid contents, fish meal has higher concentrations of amino acids (lysine [4.6 vs. 2.3], methionine +

cysteine [2.2 vs. 1.8], threonine [2.6 vs. 1.8], and tryptophan [0.6 vs. 0.4]) compared to infertile eggs. Compared to meat bone meal, infertile egg meal also exhibits lower crude protein and essential amino acid contents. Meat bone meal typically has crude protein of 52.37%, lysine 2.97%, methionine + cysteine 1.17%, threonine 1.69%, and tryptophan 0.34% (Navarro et al., 2018). Compared to soybean meal, a plant-based protein that is the main source of protein for broiler chickens, infertile egg meal also has lower crude protein and essential amino acid contents. Soybean meal has crude protein of 47.98%, lysine 3.00%, methionine + cysteine 1.27%, threonine 1.81%, and tryptophan 0.65% (Navarro et al., 2018). Additionally, Gaikwad et al. (2026) conducted a comparative analysis of the nutritional composition of hatchery discarded whole egg meal and soybean meal. On a dry matter basis, the hatchery discarded whole egg meal exhibited higher levels of ether extract (26.5% compared to 0.9%), total ash (18% compared to 8%), gross energy (18.1 MJ/kg compared to 11.2 MJ/kg), aflatoxin (16 ppb compared to 8 ppb), calcium (9% compared to 0.46%), phosphorus (0.4% compared to 0.09%), and methionine (1.10% compared to 0.59%). Conversely, it contained lower amounts of crude protein (34.1% compared to 46.0%) and lysine (2.10% compared to 3.09%). Soybean meal makes up a significant proportion of broiler feed, around 30-40% (Choi et al., 2021; Haruni et al., 2025; Suprayogi et al., 2025a,b). Given that egg protein contains high biological value (99.9%) and the amino acid profile (Choi et al., 2021), it has potential to replace the fish meal and soybean meal from poultry rations. Moreover, since animal-based protein has better digestibility and anabolic properties (Berrazaga et al., 2019), the use of infertile eggs, which are hatchery waste, is expected to reduce feed costs and protect the environment without compromising broiler productivity (Akinola et al., 2020; Ratriyanto et al., 2020; Gaikwad et al., 2026).

Many studies have reported the use of infertile egg meal as an alternative protein source for broiler chickens. In a study by Ratriyanto et al. (2020), infertile egg meal was included in feed at up to 8% without negatively impacting growth performance of broiler chickens. Likewise, Choi et al. (2021) used infertile egg meal as a substitute for fish meal (5% fish meal in the feed). They noted that completely replacing fish meal with infertile egg meal had no adverse impact on broiler productivity and health. Furthermore, Suprayogi et al. (2025a) reported that using infertile egg meal as a substitute for maize and soybean meal at 8% in the feed did not negatively impact broiler performance. The infertile egg meal can be used to completely replace 72% fishmeal in broiler diets (Akinola et al., 2020). This substitution can help save on feed costs without significantly affecting the overall performance of the chickens. In line with the aforementioned study, Gaikwad et al. (2026) used infertile egg (hatchery-discarded whole egg) meal at 5% in feed as an alternative protein source (replacing soybean meal up to 14% in broiler diets). This treatment resulted in improvements in body weight gain, feed conversion ratio (FCR), and nutrient utilization.

Consistent with this study, Choi et al. (2021) found that increasing the inclusion levels of infertile egg meal from 0% to 5.0% to replace fish meal in the diet did not negatively affect the growth performance of broiler chickens. Furthermore, replacing fish meal with infertile egg meal had no adverse effects on plasma measurements, immune organ index and tibia characteristics.

PREPARATION OF INFERTILE EGGS TO BE USED AS A DIETARY INGRE-DIENT FOR BROILERS

To ease mixing infertile eggs with other feed ingredients during the feed formulation process, infertile eggs may be processed into powder.
Powdered feed ingredients with low water content also make it easier for farmers to store the feed ingredients before use. Based on these considerations, infertile eggs are generally converted into dry powder using freeze-drying (Handayani et al., 2025), spray-drying (Esmailzadeh et al., 2013), or oven-drying method (Suprayogi et al., 2025 a,b). The use of freeze-drying and spray-drying method typically incurs costs that can increase feed production costs.
Compared to the two drying methods, oven-drying is cheaper and does not burden farmers' feed costs (Suprayogi et al., 2025a,b). To facilitate and speed up the drying process, infertile eggs need to be added with other ingredients that can absorb the water content in the eggs, such as wheat flour (Suprayogi et al., 2025a,b) or rice bran (Haruni et al., 2025). However, the addition of other ingredients to the infertile egg during the manufacturing process and the

percentage of added ingredients must be done with careful consideration.

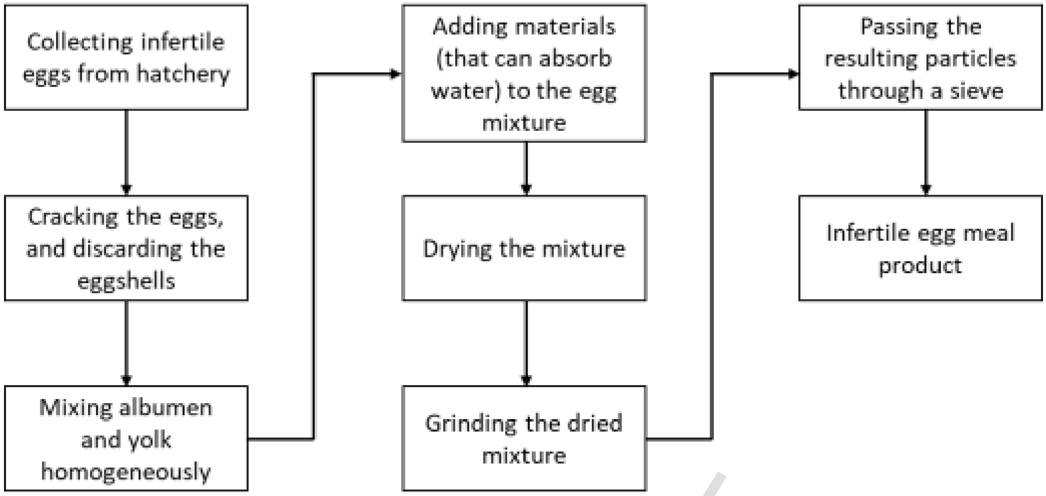

Figure 1. Production of infertile egg meal

Table 2.
Effect of infertile egg meal inclusion in feed on broiler chickens

Levels of infertile egg meal in feed	**Effects of infertile egg meal on broiler chickens**		**References**
	Production performances	**Physiological condition and health**	
0.7% added to feed	Maintained the growth performance of high-density-induced stress broilers at levels comparable to broilers raised at normal density	Protected broilers from stress-induced oxidative damage	Anggraeni et al. (2025)
5% (replacing SBM up to 14%)	Improved growth rate, FCR, apparent utilization coefficient of crude protein, ether extract, and calcium	Improved erythrocytic antioxidant activities (catalase and superoxide dismutase [SOD])	Gaikwad et al. (2026)
4% (replacing SBM)	Increased growth rate of low-weight broiler chicks	Improved erythropoiesis, lipid metabolism, antioxidant defenses, small intestinal structure, and lesion scores in low-weight broiler chicks	Handayani et al. (2025)
4% (replacing SBM)	Enhanced digestibility of crude protein and crude fat in low-weight broiler chicks	Not measured	Haruni et al. (2025)
8% (replacing SBM + maize)	Improved feed intake, weight gain, FCR, and digestibility of dry matter, organic matter, crude protein and ether extract	Improved digestive organ development	Suprayogi et al. (2025b)
8% (replacing SBM + maize)	Increased carcass and breast meat weights and improved fatty acid and amino acid profiles in breast meat	Not measured	Suprayogi et al. (2025)
8% (replacing SBM + maize)	Supported optimal growth performance through improved nutrient digestion and absorption	Enhanced the digestive tract development	Ratriyanto et al. (2021)
5% (replacing fish meal up to 100%)	Improved lipid stability of meat, while had no adverse effects on growth performance, breast meat quality, and tibia characteristics	Had no adverse effects on plasma measurements, relative organ weight, and immune organ index	Choi et al. (2021)
8% (replacing SBM + maize)	Improved body weight gain and feed efficiency and reduced feed cost per kg body weight gain of starter broilers	Not measured	Ratriyanto et al. (2020)
5% (replacing fish meal up to 100%)	Reduced feed cost and increased profitability	Improved protein utilization, blood parameters, and amino acid balance	Akinola et al. (2020)

Akhirini et al. (2021) added 10% wheat flour and 10% palm oil to the infertile egg during manufacturing process, and found that the resulting infertile egg meal contained 48.38% crude protein.In another study, Haruni et al. (2025) added 10% rice bran to infertile eggs and produced an infertile egg meal product with a crude protein content of 34.3%. Besides the price, the proportion and nutritional composition of the added ingredients should be considered carefully as they may affect the nutriational composition as well as production cost of the infertile egg powder.

Fig. 1 illustrates the simple process of preparing infertile eggs (as a byproduct of commercial poultry hatchery) into infertile egg meal that is ready to be used as feed for broiler chickens (Suprayogi et al., 2025a,b).

BENEFICIAL EFFECTS OF INFERTILE EGG MEAL ADMINISTRATION IN FEED ON BROILER CHICKENS

Previous study has reported that egg meal exhibits growth-promoting and functional properties that are beneficial for broiler chickens. Indeed, the use of egg meal (at 60 g/kg) in a starter diet had a positive effect on growth performance, intestinal morphology, and microbiology of broiler chickens. Despite its positive impact on broiler growth and health, the use of egg meal as a feed ingredient can substantially increase feed costs, thereby potentially burdening the broiler farmers (Esmailzadeh et al., 2016). Considering that the nutritional and functional components are similar between infertile eggs (waste from poultry hatcheries) and table eggs (Ratriyanto et al., 2021), the use of infertile egg meal as a growth-booster and functional feed ingredient for broiler chickens can maximize productivity and health without increasing production costs. Table 2 present some beneficial effects of the infertile egg meal on the growth performance and health of broiler chickens.

The increased growth rate in broiler chickens fed infertile egg meal is often attributed to the increased absorptive surface area and preserved intestinal epithelial integrity. These physiological benefits translate into better nutrient assimilation and, consequently, superior growth outcomes (Handayani et al., 2025). In a study by Ratriyanto et al. (2021), the improvements in growth performance and digestibility in broiler chickens fed infertile egg meal were associated with the improved digestive tract development, resulting in optimal digestive and absorptive function in the broilers. In such cases, the improvement in digestive tract development is closely related to the high nutritional value and high availability of nutrients in the egg meal, which are necessary to support the high growth rate of the chickens' digestive tract and body. More specifically, infertile eggs are rich in high-quality protein (especially albumin), lipids, fats, maternal antibodies, antioxidants, and bioactive components such as essential fatty acids and bactericidal enzymes, which are essential for the development of the chicken's digestive tract. The high content of available essential amino acids and minerals in infertile eggs also plays an important role in improving the growth rate of broiler chickens (Choi et al., 2021). The administration of infertile egg meal also increased the protein and energy content of the broiler diets. This resulted in higher protein intake and higher energy intake (Ratriyanto et al. (2020). Such increased nutrient supply supports a higher growth rate of broilers. Besides growth rate, infertile egg meal administration has been reported to increase carcass and breast weights of broiler chickens. In this respect, Suprayogi et al. (2025a) noticed that the superior amino acid profile of the infertile egg meal diets, particularly essential amino acids, likely contributes to the increased body weight, carcass, and breast weights.

The use of infertile egg meal in feed has been reported to improve the meat quality of broiler chickens, in this case increasing stearic acid content, doubling the levels of α-linolenic acid, an essential omega-3 fatty acid and significantly reducing oleic acid content in broiler meats. Apart from that, infertile egg meal also increased the concentration of specific amino acids in the breast meat, such as threonine, arginine, glycine, and alanine (Suprayogi et al., 2025a). Changes in the fatty acid profile of chicken meat are closely related to the unique fatty acid profile of the infertile egg-enriched feed, which leads to a major shift in the meat's composition, characterized by an increase in saturated (stearic acid) and polyunsaturated fatty acids (PUFA; particularly α-linolenic acid) and a decrease in monounsaturated fatty acids (MUFA; particularly oleic acid). Related to amino acid changes in meat, the highly digestible protein in infertile egg meal likely enhanced the availability and absorption of amino acids (Suprayogi et al., 2025a). Infertile eggs have also been reported to improve antioxidant activity in chickens. Gaikwad et al. (2026) explained that eggs act as a natural antioxidant due to the presence of various bioactive components, which may be responsible for this increase in antioxidant activity. In line with this, Handayani et al. (2025) reported that providing infertile egg meal increased SOD and lowered malondialdehyde (MDA) levels in broilers. They further explained that proteins found in eggs, such as ovalbumin, ovotransferrin, and phosvitin, possess inherent antioxidant properties. Bioactive peptides derived from these proteins can reduce the oxidative state in poultry by stimulating the body's natural antioxidant enzymes, such as SOD. Egg yolk is also rich in carotenoids, specifically lutein and zeaxanthin. These carotenoids act as effective antioxidants by neutralizing free radicals, stabilizing cell membranes, and preventing the peroxidation of lipids. This enhances the overall antioxidant defense system, especially during periods of high metabolic activity and growth. Eggs are a good source of selenium, which is highly concentrated in the yolk. Selenium is essential for the synthesis of crucial antioxidant enzymes and selenoproteins, including glutathione peroxidase (GPx) and thioredoxin reductase (TRxR). These enzymes protect cells from oxidative stress and the lipid oxidation of cell membranes (Anggraeni et al., 2025).

Dietary inclusion of infertile eggs has been revealed to promote erythropoiesis in broiler chickens. Such capability is attributed to the high bioavailability of certain nutrients found in infertile eggs, which are essential for the production of red blood cells (Handayani et al., 2025). Certain nutrients include essential amino acids (histidine and lysine) and hematopoietic micronutrients (such as iron, copper, folate, and vitamins B2 and B12) are crucial for several processes involved in red blood cell production, such as the synthesis of globin structures, the production of heme, and the growth of erythroid progenitor cells. Therefore, by supplying these vital nutrients, infertile egg meal supports and enhances the erythropoietic function in broiler chicks. With particular regard to the capacity of infertile eggs in improving lipid metabolism, the quality protein and phospholipids in infertile egg meal may help to activate lipoprotein lipase, an enzyme that breaks down triglycerides, thus increasing their use as an energy source. In addition, the highly bioaccessible phospholipids from eggs are preferentially transported into high-density lipoprotein (HDL). The presence of choline and vitamin B12 in infertile eggs also supports HDL production and functionality. The study also reported improvements in small intestinal structure, and lowered lesion scores in broilers given infertile egg meal (Handayani et al., 2025). The protective and restorative effects of infertile egg meal on the intestine are attributed to its high bioavailability of essential amino acids that are crucial for the proliferation of enterocytes (intestinal cells), tissue repair, and maintaining the overall integrity of the intestine. The presence of bioactive compounds like phospholipids is also responsible for the improvement of small intestinal structure, and lowered lesion scores. As fundamental components of cell membranes, phospholipids help maintain the fluidity and structural stability of enterocytes, which strengthens the gut barrier (Chen et al., 2019).

Despite its positive impacts, the use of infertile egg meal as a protein source in feed also has the potential to negatively impact broiler chickens if applied at high levels. Providing infertile egg meal at 7.5 or 10% of the feed increases blood triglyceride and cholesterol levels which could negatively affect bird health and carcass quality (Gaikwad et al., 2026). Suprayogi et al. (2025a) also reported increased abdominal fat in broiler chickens fed infertile egg meal at 8% of the feed. The increase in abdominal fat is linked to the higher total fat and metabolizable energy content of the infertile egg meal-supplemented diets. Note that dietary energy that exceeds the requirements for growth is generally stored as adipose tissue. Supplementing broiler diets with infertile egg meal can also lead to higher ammonia concentrations in the litter due to increased protein intake and subsequent nitrogen excretion (Haruni et al., 2025). The higher consumption of a protein-rich diet leads to a greater nitrogen intake. In poultry, unused or excess protein is excreted as uric acid. Microbes in the litter then break down this uric acid, which forms ammonia. Although protein digestibility was improved in the infertile egg meal-fed chickens, it is possible that nitrogen retention was limited by metabolic needs, resulting in the excretion of excess nitrogen and consequently, higher ammonia production (Haruni et al., 2025).

Although this study presents data on the use of infertile egg meal as an alternative protein source for broiler chickens, research in this area remains limited. Additionally, the absence of long-term feeding trials and the lack of large-scale commercial validation pose significant concerns regarding the incorporation of infertile eggs in broiler nutrition. Beyond the limited number of published studies, a further issue is that the majority of research evidence in this review originates predominantly from studies conducted by the same research group. Therefore, caution is warranted when generalizing findings about the use of infertile egg meal in broiler nutrition. Further research is required to substantiate the beneficial effects of infertile egg meal on broiler chickens, encompassing varying levels of its use, diverse feed and nutrient compositions, and different environmental conditions.

CHALLENGES AND FUTURE PERSPECTIVES OF INFERTILE EGG MEAL AS A PROTEIN-RICH FEED INGREDIENT FOR BROILER CHICKENS

Infertile egg meal has great potential as a protein-rich feed ingredient. However, several challenges limit its use. One major challenge is the variation in nutrient composition. Like other alternative protein sources, the nutritional values of infertile egg meal can fluctuate depending on processing methods (Esmailzadeh et al., 2013; Suprayogi et al., 2025a). Currently, the dietary inclusion levels of infertile egg meal exhibit inconsistency across broiler studies (Akinola et al., 2020; Choi et al., 2021). In light of this issue, it is essential to standardize and ensure consistent nutritional quality of infertile egg meal to optimize its dietary inclusion levels and thereby achieve maximum broiler productivity.

Another challenge involves the potential for contamination by harmful microorganisms during the hatching process (Suprayogi et al., 2025a). Infertile eggs, as a byproduct of hatchery operations, may serve as reservoirs for pathogenic microorganisms, including *Salmonella* sp., *Escherichia coli*, and *Clostridium* sp. Likewise, eggs may serve as a vector for mycotoxins. These mycotoxins can be transmitted into eggs through the broiler feed supply chain. When chickens ingest feed tainted with mycotoxins, these compounds or their metabolic byproducts may be transferred into edible tissues and products, including eggs (Tolosa et al., 2021). Therefore, it is crucial to ensure that infertile eggs are free from harmful bacteria as well as mycotoxins before being fed to broiler chickens.

Pathogen control must be implemented comprehensively from the upstream hatchery stage to the downstream infertile egg meal production process. In hatcheries, disinfection is commonly employed, utilizing methods such as formaldehyde fumigation and gas-phase hydroxyl radical treatment, to manage pathogens on eggs. This ensures that infertile eggs collected from hatcheries do not serve as a pathogen source for broiler chickens (Dhillon et al., 2025). At the downstream stage, drying or thermal treatment is frequently used to control pathogens. However, this approach can render infertile egg meal vulnerable to cross-contamination during subsequent cooling, packaging/loading, and transportation to farms (Obe et al., 2023). Although economically efficient, thermal treatment does not completely eradicate pathogens and mycotoxins. While freeze-drying effectively preserves bioactive compounds, it is less effective for sterilization and incurs substantial costs. Conversely, autoclaving guarantees microbiological safety but may adversely affect the nutritional quality of infertile egg meals (Gaikwad et al., 2026). Alternative methods, such as the incorporation of chemical additives, can be employed to control pathogens during the infertile egg meal production process and offer protection post-thermal processing. Commonly used chemical additives include formaldehyde-based products, organic acids, and essential oils (Obe et al., 2023).

When incorporating infertile egg meal into broiler feed, it is imperative to consider its adverse effects on meat quality parameters and metabolic implications. Although there is an observed enhancement in growth performance and carcass yield, the inclusion of infertile egg meal resulted in increased abdominal fat deposition in broilers, attributable to the high total fat and saturated fat content of infertile egg meal (Suprayogi et al., 2025). Furthermore, infertile egg meal influences meat color, leading to increased lightness and decreased redness, as well as alterations in post-mortem pH, which may affect consumer acceptability (Choi et al., 2021). Consequently, meticulous diet formulation is required to balance energy levels and avert undesirable changes in body composition of broiler chickens. While the inclusion of infertile egg meal does not negatively impact hematological indices, the degree of its immunomodulatory effects remains variable (Akinola et al., 2020). Moreover, certain studies indicate substantial improvements in antioxidant status and stress resilience, whereas others report only moderate effects. These discrepancies may be attributed to differences in the quality of infertile egg meal, basal diet compositions and protein digestibility (Anggraeni et al., 2025; Handayani et al., 2025).

Economic considerations also pose significant obstacles when using infertile egg meal for broilers. Alternative protein sources often have higher production costs or limited large-scale availability compared to conventional feeds such as soybean meal (Grigore et al., 2025). Cost-effective production infrastructure and supply chains for infertile egg meal must be developed to be competitive. In term of regulatory compliance, infertile eggs intended for broiler chicken feed must be devoid of harmful substances and safe for consumption. Consequently, their use in animal feed must adhere to regulatory standards, which include processing according to specified protocols and ensuring they are free of pathogens and toxins (USDA, 2013). As a byproduct of hatcheries, infertile egg meal is highly prone to microbial contamination and mycotoxins originating from broodstock feed, and it is notably perishable (Abdul-Shaheed et al., 2019; Ramadan et al., 2025). Consequently, the use of infertile eggs from hatcheries as a protein-rich animal feed ingredient necessitates meticulous handling and adherence to a rigorous Hazard Analysis and Critical Control Point (HACCP) framework. Additionally, ensuring traceability of hatchery-derived egg meal from the hatchery to the processing facility, alongside the standardization of processing methods, is imperative to maintain the quality and safety of infertile egg meal (Asiedu et al., 2022). Certain countries prohibit the use of hatchery waste, such as infertile eggs, as animal feed due to the potential risk of pathogen transmission (Ramadan et al., 2025). Conversely, other countries permit its use under stringent regulations. For example, European Union regulations allow infertile eggs to be processed into feed for farmed animals provided they undergo heat treatment at a minimum of 121 °C for 3 minutes. This process effectively eliminates nearly all vegetative and spore forms of pathogens, ensuring the complete inactivation of the most resistant biological hazards (EFSA Panels on Animal Health and Welfare (AHAW) & on Biological Hazards (BIOHAZ), 2011). The utilization of agro-industrial byproducts in broiler production typically enhances sustainability from a life cycle analysis (LCA) perspective. The feed production phase significantly contributes to the carbon footprint in poultry systems. Replacing high-emission ingredients such as soybean meal, which involves considerable land use and GHG emissions, with infertile egg meal reduces carbon intensity. Additionally, infertile egg meal decreases the water footprint, as conventional protein-rich feed ingredients like soybean require extensive irrigation (Sugiharto et al., 2026). Consequently, the use of infertile egg meal can diminish reliance on traditional protein feeds, which are linked to environmental concerns (Grigore et al., 2025). Dietary inclusion of infertile egg meal for broilers can also support a circular economy approach by enhancing the value of poultry hatchery byproducts; however, environmental impact assessments are necessary. Indeed, the inclusion of infertile egg meal in broiler chicken feed can lead to an increase in atmospheric ammonia concentrations (Haruni et al., 2025). This finding indicates that potential environmental management challenges must be addressed alongside dietary optimization.

Taken all together, while challenges related to processing safety, optimal dietary inclusion levels, and environmental management require attention, infertile egg meal demonstrates substantial future potential as a sustainable, multifunctional protein ingredient. Future research and technological innovation focused on optimizing inclusion and processing, assessing environmental impacts, and developing supporting infrastructure are essential to advancing the use of infertile egg meal in broiler nutrition.

CONCLUSIONS

Infertile eggs are a byproduct of poultry hatcheries that have great potential as an alternative, low-cost protein source for broiler chickens. Using infertile egg as a feedstuff can potentially reduce dependence on soybean meal, lower production costs, and positively impact the environment by reducing GHG emissions and odors. However, challenges include variations in nutritional value due to processing methods and potential contamination by pathogenic microbes and mycotoxins. Including infertile egg meal in broiler diets can improve growth performance, digestibility, meat quality, antioxidant activity, erythropoiesis, and lipid metabolism without negative effects. However, high inclusion levels may increase blood triglycerides, cholesterol, abdominal fat, and ammonia in litter. Future research should focus on standardizing processing methods, ensuring safety, and developing cost-effective production and supply chains to advance the use of infertile egg meal in broiler nutrition.

AUTHOR CONTRIBUTIONS

Conceptualization, S.S. and D.N.A.; Investigation, validation, writing-original draft preparation, S.S.; Review and editing, M.M.S., T.U. and D.N.A.

DATA AVAILABILITY STATEMENT

Data contained within the article.

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CONFLICT OF INTEREST

The authors have no conflict of interest.

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OD OTPADA DO HRANE: PREGLED NAJNOVIJIH SAZNANJA O NEOPLOĐENOM JAJETU KAO PROTEINSKI BOGATOM HRANIVU ZA TOVNE PILIĆE

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Sažetak: Neoplođeno jaje je nusproizvod živinarskih inkubatora sa velikim potencijalom kao alternativni izvor proteina za tovne piliće. Ovaj pregled daje najnovije informacije o nutritivnoj vrednosti, metodama prerade i korisnim efektima upotrebe brašna od neplodnih jaja u ishrani brojlera. Neplođena jaja su po nutritivnim vrednostima uporediva sa plodnim i konzumnim jajima, jer sadrže visok nivo proteina, esencijalnih masnih kiselina, vitamina i minerala. Metode prerade poput sušenja raspršivanjem, sušenja u rerni i liofilizacije mogu pretvoriti neplođena jaja u prah pogodan za formulaciju hrane za brojlere. Istraživanja su pokazala da uključivanje praha od neoplođenih jaja može poboljšati proizvodne rezultate, svarljivost hranljivih materija, zdravlje creva, antioksidativni status i kvalitet mesa kod brojlera, bez negativnog uticaja na troškove proizvodnje. Međutim, izazovi poput varijacija u nutritivnom sastavu usled različitih metoda prerade i potencijalne mikrobne kontaminacije tokom procesa inkubacije moraju biti rešeni. Buduća istraživanja treba da se fokusiraju na optimizaciju nivoa uključivanja, metode prerade i procene uticaja na životnu sredinu kako bi se unapredila održiva upotreba ovog vrednog izvora proteina u ishrani brojlera.

Ključne reči: *alternativna hrana za životinje, živina, nusproizvod živinarstva, sojina sačma, održivost*

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