CALCIUM SOURCES FOR SUSTAINABLE POULTRY NUTRITION: A REVIEW

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Abstract

Calcium plays a central role in poultry nutrition, particularly for skeletal development, bone strength and eggshell quality. In view of the growing demands for both performance and sustainability in poultry production, a better understanding of the various sources of calcium available is becoming increasingly essential. This systematic review offers a critical analysis of traditional sources (such as limestone and phosphates), sources of animal origin (oyster shells, recycled eggshells) and alternative sources derived from agro-industrial by-products. The aim is to compare their bioavailability, digestibility, and effects on the zootechnical performance of broilers and laying hens. Beyond chemical composition, factors such as particle size and interaction with digestive physiology, notably the role of the gizzard, strongly influence calcium absorption efficiency. By cross-referencing recent data from scientific literature, this review provides insight into the comparative evaluation of calcium sources and underscores the need for more precise and tailored dietary formulations. The aim is to provide researchers and poultry professionals with concrete elements for optimizing calcium supplementation strategies, in a perspective that is both efficient, sustainable and economically viable.

Keywords*: dietary calcium sources, broilers, laying hens, calcium bioavailability, mineral and organic sources*

INTRODUCTION

Calcium nutrition in poultry is a priority field of research due to the vital importance of this mineral in skeletal growth, bone strength, eggshell quality, and overall bird health. Historically focused on the use of classic mineral sources such as limestone or oyster shells, research has gradually evolved towards the exploration of alternative, more sustainable sources, including recycled eggshells and certain agro-industrial by-products [20, 46]. In this context, the interaction between calcium and other essential minerals, such as phosphorus, is attracting increasing attention due to its role in bone metabolism and its contribution to zootechnical performance, while also raising environmental concerns [2, 20]. Worldwide, calcium deficiencies in poultry diets result in significant economic losses, primarily due to poor egg quality and

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locomotor system disorders [3, 5], underscoring the need for rational optimization of supplementation.

Despite their widespread use, inorganic sources such as calcitic limestone and phosphates show significant variability in terms of bioavailability and digestibility [24, 25]. These differences, influenced by various factors such as particle size and solubility, pose a significant challenge for formulating balanced feeds. Furthermore, comparative data on zootechnical performance associated with animal sources (such as oyster shells and eggshells) versus mineral sources remain incomplete [14, 24, 36]. The role of the gizzard in calcium release and absorption is increasingly recognized as a crucial factor, especially in the context of precision nutrition adapted to different production phases.

The integration of agro-industrial residues as potential sources of calcium is a promising, yet little-explored, avenue for meeting the imperatives of sustainability and organic waste recovery [22, 28, 55]. However, the heterogeneous results reported in the literature regarding the impact of these different sources on growth, egg quality, or bone strength make it difficult to adopt standardized recommendations [3, 32, 41]. This lack of uniformity limits the effectiveness of current nutritional formulations and hinders progress towards more sustainable poultry farming.

The conceptual framework of this review is based on an integrated approach that combines the physicochemical properties of different calcium sources, such as mineral composition and particle size, with their biological effects, notably on calcium digestibility, retention and utilization in poultry [14, 20, 24]. Particular attention is paid to the role of the gizzard in calcium solubilization, as well as to the impact of the source (mineral or organic) on its absorption in the digestive tract [36, 60]. This analytical framework is based on theoretical models of mineral metabolism and nutrient bioavailability in monogastrics [13, 20].

This systematic review critically compares the different sources of calcium - whether mineral, animal, or alternative - used in poultry diets. It aims to better assess their efficacy in terms of bioavailability and digestibility, as well as their influence on productivity, shell quality and bone health, in both broilers and layers. Based on the most recent data from peer-reviewed studies directly related to calcium sources in poultry farming. The analysis follows a thematic logic structured around the types of sources - mineral, animal, and sustainable alternatives - and their respective effects on zootechnical performance. This work aims to provide a clear and well-founded synthesis of available knowledge, in order to support applied research and innovative nutritional practices in poultry production [46, 63].

CALCIUM SOURCES

Calcium intake in poultry feed is primarily based on mineral sources, as ingredients of plant origin contain very little [16]. Limestone is by far the most widely used additive, due to its availability, moderate cost, and high calcium concentration. Other inorganic sources, such as calcium phosphates (monocalcium, dicalcium, or monodicalcium) and oyster shells, are also commonly incorporated into food formulations. In addition, inevitable animal by-products, such as bone meal or poultry meal, and some vegetable oilcakes, notably canola or soya, can make a significant contribution to meeting calcium requirements. However, they are rarely used as the primary source.

LIMESTONE AS A SOURCE OF CALCIUM

Limestone is widely recognized as the most commonly used source of calcium in bird diets, primarily due to its high calcium content and economic availability. Its chemical composition is essentially based on calcite ($CaCO_3$). However, it may contain other compounds such as aragonite, dolomite ($CaMg(CO_3)_2$), and calcium oxide (CaO), depending on its geological provenance [56]. The diversity of its formation, including chemical precipitation, marine biological activity, and lithification of carbonate sediments, contributes to the variability of its mineral composition and crystalline structure.

Geological classification generally distinguishes limestones according to their depositional environment: platform, basin, or geosyncline. Their appearance, including color (such as beige or gray), is often influenced by the presence of impurities, including clay, metal oxides, or organic matter.

In nutritional matrices, the calcium content of limestone is often estimated at 380 g/kg. However, analyses show a variation ranging from 304 to 420 g/kg, depending on the sample [6, 47]. Gilani *et al.* [25] reported a range of 333 to 400 g/kg, with an average of 379 g/kg, in a study of 641 samples from 40 countries. The theoretical maximum calcium content of pure calcium carbonate ($CaCO_3$) is 400.4 g/kg. Higher values may indicate CaO contamination, while lower values signal the presence of non-calcium elements.

On average, limestone accounts for up to 70% of the calcium requirements in standard broiler diets. It has long been considered the benchmark for calcium bioavailability, often assumed to be 100%. However, contemporary approaches prioritize assessing actual digestibility, particularly at the ileal level, to estimate the fraction that the animal can assimilate. Several studies show that this digestibility can vary considerably depending on various parameters: geological source [6, 18, 67], particle size [6, 7, 67], in vitro solubility [67], phosphorus level in the ration [6], and age of the birds [8, 9]. Reported ileal calcium digestibility rates thus vary from 27% to 77%.

The mineral composition of limestone also varies according to its origin. For example, dolomitic limestone, which contains up to 12% magnesium [57], interferes with calcium absorption through competition at intestinal absorption sites. Additionally, magnesium can bind to calcium, thereby reducing its bioavailability. These interactions explain why dolomitic limestone is not recommended for poultry feed.

Finally, particle size and solubility directly influence the release and absorption of calcium. Zhang and Coon [67] observed that limestone retention in the gizzard varied according to source, despite similar particle size, due to differences in in vitro solubility (5.90 g vs. 3.81 g). Similarly, Anwar *et al.* [8] found variations in ileal calcium digestibility among three limestone samples of the same grain size, with coefficients of 0.54, 0.58, and 0.61. These variations underscore the complexity of factors influencing calcium bioavailability, highlighting the need for a specific evaluation of each source before it is incorporated into food formulations.

OTHER INORGANIC SOURCES OF CALCIUM

Oyster shells, an alternative mineral source to limestone in poultry feed, also contain calcium carbonate. Their calcium content, ranging from 344 to 390 g/kg [16, 47], is comparable to that of limestone. According to Augspurger and Baker [12], the bioavailability of calcium in these shells is equivalent to that of limestone, although this also depends on factors such as particle size. Anwar *et al.* [10] have shown that coarse particles (1.0-2.0 mm) are more digestible (coefficient of 0.56) than fines (<0.5 mm), which have a coefficient of just 0.33. Other studies indicate that larger particles, which dissolve more slowly, improve calcium availability compared to fine particles [53]. In general, oyster shells improve eggshell quality in a way comparable to limestone [49].

Dicalcium phosphate ($CaHPO_4$), industrially produced by neutralizing calcium hydroxide with phosphoric acid, represents another important source. Its dihydrate form ($CaHPO_4$-$2H_2O$) contains around 220 g of calcium and 190 g of phosphorus per kilogram [16]. Its variants, such as the hemihydrate and anhydrous forms, have different nutrient contents [64]. This product can also be obtained by precipitation from bone, notably in the manufacture of gelatin [59]. It has been suggested that dicalcium phosphate from bone has a higher biological value than commercial forms [59].

ANIMAL SOURCES OF CALCIUM

Specific raw materials of animal origin, such as meat-and-bone meal, fish meal, or poultry by-products, provide a significant amount of calcium in poultry feed. On average, meat-and-bone meal contains around 103 g/kg of calcium [39]. However, this content varies significantly depending on the raw materials and technological processes used [8, 9, 65]. The final composition depends on the ratio between bone and soft tissue. Thus, these products are classified as either meat meal (protein > 55%, phosphorus < 4.4%) or meat and bone meal (protein < 55%, phosphorus > 4.4%).

Fishmeal is produced from fish not intended for human consumption, via stages such as cooking, pressing, drying, and grinding. A similar process is used to obtain poultry by-product meal, based on the rendering of slaughterhouse remains.

VEGETABLE SOURCES OF CALCIUM

In poultry feed formulations, plant ingredients are mainly valued for their energy or protein content, their calcium contribution being limited. Among the notable exceptions, canola meal (6.8 g/kg) and rice bran (7.0 g/kg) are the richest plant sources of calcium [16]. In comparison, the calcium content of soybean meal, one of the main protein concentrates, is 2.8 g/kg, while that of cereals is negligible.

BIOAVAILABILITY AND DIGESTIBILITY OF CALCIUM SOURCES

Numerous studies comparing mineral calcium sources of animal origin have shown the high bioavailability of dicalcium phosphate and fine limestone. Egg and oyster shells show similar, if not slightly lower, digestibility in broilers and laying hens [13, 24, 48]. The application of advanced analytical techniques, such as XRD and FTIR, in recent research is enhancing the understanding of their physicochemical properties and their impact on bioavailability [22]. Including real or apparent digestibility coefficients for different ages and calcium sources provides key data for diet formulation [24]. Generally, dicalcium phosphate and acceptable limestone offer higher bioavailability than coarse limestone or some animal sources [20, 21, 24]. Calcium from eggshell shows high digestibility and bioavailability, often comparable to or better than oyster shell or other inorganic sources, in broilers and laying hens [26, 48, 52]. Organic shellfish meals, such as mussels and oysters, exhibit high bioavailability in quail and chickens, confirming their potential as an alternative source of calcium [21, 35]. Some studies suggest that the chemical form of calcium (citrate, lactate, acetate) has a minimal impact on its bioavailability, indicating that physical form and particle size play a more significant role [13].

ROLE OF PARTICLE SIZE (GRANULOMETRY) ON CALCIUM RELEASE AND RETENTION

There is strong evidence that coarse calcium particles (such as limestone, oyster, or eggshell) improve calcium retention in the gizzard, enhancing eggshell quality and bone strength in laying hens [21, 24, 34, 36]. Studies show that these particles prolong calcium release according to physiological needs during shell formation [33, 60, 68]. Particle size also influences bone mineralization in broilers and their calcium metabolism, particularly when coarse oyster shell increases the calcium content of the tibia [14]. Fine limestone particles are generally more soluble and digestible in vitro, but coarser particles remain longer in the gizzard, potentially increasing calcium availability during shell formation [21, 24, 36, 46]. Large oyster and eggshell particles improve bone mineralization and shell quality, probably through prolonged calcium release [14, 36, 52]. However, optimal particle size remains subject to debate, with some studies showing little difference between fine and medium particles [15, 60]. Particle size also influences food intake and digestive development, thus indirectly affecting calcium utilization [11].

SUSTAINABLE AND ALTERNATIVE CALCIUM SOURCES

Research highlights the potential of eggshell waste, bone dust, and industrial residues as sustainable and efficient sources of calcium, without adversely affecting the performance or health of broilers and laying hens [32, 43, 55, 58]. These alternatives promote waste recovery and environmental sustainability while maintaining or improving digestibility and calcium retention [28, 55]. Studies also emphasize their economic benefits and positive impact on animal welfare 22, 27]. Several research studies have investigated the use of eggshell waste, bone dust, and marine residues as sustainable sources of calcium, showing equivalent performance to conventional mineral sources and potential environmental benefits [28, 32, 43, 55, 58]. Figuil limestone and other regional limestones are proposed as sustainable alternatives to shellfish meal in chicken feed [22]. Industrial by-products, such as eggshell waste, are proving to be safe and efficient sources of calcium, supporting a circular economy in avian nutrition [28, 55]. Despite promising results, many studies have limited sample sizes or short durations, which limits the assessment of long-term effects on production and health [43, 58]. Variability in processing methods and quality control of waste-derived calcium sources may affect consistency and safety, which is not sufficiently considered 28.

EFFECTS ON BROILER GROWTH PERFORMANCE AND BONE HEALTH

Several studies have shown that the calcium source and concentration influence chicken growth, feed efficiency, and bone mineralization, with a preference generally given to limestone and dicalcium phosphate for optimal results [1, 20]. The interaction between calcium levels and their source is crucial, as excess calcium can adversely affect performance [23]. The addition of phytase improves calcium digestibility and bone health, especially in low-phosphorus diets [2, 20]. Broiler growth, feed intake, and feed conversion were generally unaffected or improved by replacing limestone with calcium sources from eggshells or marine shells [22, 30, 48, 58]. However, high levels of calcium, particularly from oyster shell, can sometimes reduce performance, highlighting the importance of maintaining a calcium balance [23]. Coarser calcium particles and specific sources improve bone mineralization and skeletal strength, promoting bone health [14, 43, 44]. Supplementation with active dicalcium phosphate also enhanced weight gain and feed efficiency in broilers compared with shell powders [66]. Some studies, nevertheless, reveal minimal or no differences in growth performance between calcium sources, suggesting that calcium concentration may have a greater influence than the source [23, 48]. Most studies agree that calcium source (limestone, oyster shell, eggshell) does not significantly affect growth performance parameters such as weight gain, feed intake or feed conversion ratio when diets are balanced in calcium and phosphorus [1, 21, 30, 48]. Bone mineralization and strength are generally maintained from one source to another.

EFFECTS ON LAYING HEN PERFORMANCE AND SHELL QUALITY

The literature consistently shows that calcium source and particle size influence shell quality parameters such as thickness, breaking strength, and weight, with coarse limestone and eggshells often outperforming fine particles [34, 36, 37, 46, 68]. High levels of dietary calcium improve shell quality and reduce egg breakage, particularly in older hens [5, 51]. Combining different calcium sources can optimize production and shell quality [52, 63]. Coarse calcium particles, such as limestone gravel, oyster or eggshell, consistently improve thickness, strength, and reduce breakage rate in laying hens [33, 34, 36, 37, 46). Calcium sources in eggshells had no significant effect on egg-laying rate, but did influence shell weight and quality [29, 36, 63]. High dietary calcium intakes improved shell quality and reduced cracked eggs, especially in older hens [5, 51]. Limestone has often been found to be more beneficial than oyster shell for egg production and feed efficiency, even though both promote good shell quality [3, 41]. There is a broad consensus that calcium source and particle size influence shell quality, with coarser particles improving shell thickness, breaking strength, and reducing shell breakage [33, 34, 36, 37, 46, 63, 68]. Egg production and weight are often unaffected by calcium source, but can improve with optimal granulometry and calcium levels [5, 36, 45].

INTERACTIONS BETWEEN PHYTASE AND MINERALS

Evidence shows that phytase supplementation improves calcium digestibility by releasing phytate-bound calcium and phosphorus, especially in phosphorus-deficient diets [2, 20, 50]. An excessive dose of phytase can also increase calcium availability and reduce the need for high dietary calcium levels [50]. This practice is crucial for maximizing mineral utilization and minimizing phosphorus discharge into the environment. The interaction between calcium source, particle size, and phytase efficacy is complex and still poorly understood, with some studies showing variable responses depending on diet composition [20]. The ideal phytase dosage and its effects according to different calcium sources require further research. Moreover, the long-term impact on bone health and metabolic parameters remains poorly studied.

METHODOLOGICAL APPROACHES AND EXPERIMENTAL DESIGNS

The use of factorial designs, multiple replications, and advanced analytical methods enhances the reliability of the results of many studies [14, 24, 46]. The inclusion of in vivo and in vitro assessments (e.g., solubility tests, ileal digestibility, bone strength measurements) provides a multidimensional understanding of calcium utilization [25, 62]. There is a lack of standardized protocols for measuring calcium digestibility and retention, variations in adaptation periods, and dietary Ca:P ratios, as well as methods of calculating digestibility that affect comparability [20, 24]. Some studies rely on short-term trials or limited sample sizes, reducing statistical power and external validity [43, 58]. The absence of data on long-term production and health outcomes limits the practical applicability of some results.

OVERALL SUMMARY AND CONCLUSION

Research on calcium sources in poultry feed reveals that both mineral and animal-derived calcium are adequate, but their bioavailability, digestibility, and physiological effects vary. Dicalcium phosphate and finely ground limestone consistently offer higher calcium digestibility and bioavailability, especially in laying hens, while coarser particles such as limestone, oyster shell, or eggshell improve calcium retention in the gizzard, allowing a slower release crucial for shell formation and bone health. Eggshell calcium, often seen as a sustainable and organic option, matches or surpasses the bioavailability of traditional mineral sources, confirming its usefulness as a substitute in broiler and layer diets. The particle size significantly influences outcomes: coarse particles extend calcium availability during key phases of eggshell calcification and enhance bone strength. In contrast, fine particles are more digestible but may not release calcium as effectively during the laying cycle. There is some variability, with certain studies showing minimal differences in particle size under specific conditions, reflecting the complex interactions among bird age, calcium intake, and diet composition.

Sustainability considerations have become increasingly important, with numerous studies validating the use of industrial by-products, such as eggshell waste, bone dust, and marine shell residues, as effective calcium sources that do not compromise performance or health. These alternatives promote the principles of the circular economy by valorizing agro-industrial waste, thereby contributing to environmental sustainability without compromising nutritional quality. Nevertheless, long-term and large-scale evaluations remain limited, necessitating further research into process standardization, safety, and consistent quality assurance.

Regarding broiler performance, the calcium source and concentration significantly influence growth parameters and bone mineralization, primarily through their effects on calcium availability and phosphorus balance. Although high levels of calcium, particularly from oyster shell, can hurt feed intake and growth, optimal inclusion rates of digestible calcium sources promote skeletal health and improve feed efficiency. In laying hens, coarse calcium particles and adequate dietary calcium levels improve eggshell thickness and strength, and reduce breakage, particularly in older birds, thus improving production profitability. Limestone often provides better feed efficiency and egg production than oyster shell, although both retain appropriate shell quality. The inclusion of the phytase enzyme improves calcium and phosphorus digestibility, optimizes mineral utilization, and mitigates phosphorus excretion into the environment. However, the interaction between phytase efficiency, calcium source, and particle size warrants further elucidation.

In summary, the literature recommends balanced feed formulations incorporating suitable calcium sources, with particle sizes optimized to meet the physiological needs of broilers and layers. Sustainable calcium alternatives, such as eggshell calcium, offer promising solutions for reducing environmental impact while maintaining or improving production performance. Further research integrating long-term performance, health markers, and environmental parameters will be crucial for refining calcium nutritional strategies, aligning with the economic and sustainability objectives of the poultry industry.

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