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Enhanced Bioavailability of Nutrients in Pelleted Feeds: Implications for Performance, Health, and Meat Quality of the Broiler Chicken

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Abstract

The optimization of nutrient bioavailability in pelleted feeds is crucial for enhancing the performance, health, and meat quality of broiler chickens. This review explores the complex mechanisms by which pelleting improves nutrient availability, including physical changes in feed structure, thermal and chemical effects, and the reduction of anti-nutritional factors. It also highlights the significance of improved gut health and digestion, which contributes to enhanced nutrient absorption and utilization. The paper further discusses the implications of these mechanisms on broiler performance metrics, including growth rates, feed conversion efficiency, and overall health status. Additionally, the role of pelleted feeds in reducing feed wastage and spoilage, as well as in pathogen control, is examined. By synthesizing current knowledge on the relationship between pelleted feed formulations and nutrient bioavailability, this review underscores the importance of these processes in the context of sustainable poultry production. The findings indicate that optimizing pelleted feed formulations can significantly enhance the nutritional profile of diets for broiler chickens, leading to improved meat quality and health outcomes, ultimately benefiting the poultry industry and food security.

Keywords: Broiler, health, meat quality, nutrient bioavailability, pellet, performance

INTRODUCTION

The poultry industry is a critical component of global agriculture, providing a significant source of protein through broiler chicken production. As consumer demand for high-quality meat increases, the focus on optimizing feeding strategies to enhance nutrient bioavailability has become paramount. Nutrient bioavailability refers to the proportion of nutrients that can be absorbed and utilized by the animal after ingestion, which is influenced by various factors, including feed formulation, processing techniques, and the inherent characteristics of the feed ingredients [1]. Among these, pelleted feeds have gained widespread acceptance due to their ability to improve feed efficiency, reduce waste, and enhance the overall performance of broiler chickens [2].

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Pelleting is a feed processing technique that involves the compression and extrusion of feed ingredients into small, uniform pellets. This process not only improves the physical characteristics of the feed but also alters its chemical composition and biological availability [3]. The physical changes associated with pelleting, such as reduced particle size and improved uniformity, facilitate more effective digestion and absorption of nutrients in the gastrointestinal tract [4]. Additionally, the heat treatment involved in pelleting induces various thermal and chemical reactions, including gelatinization of starches and denaturation of

proteins, which further enhance the digestibility of feed components [5].

The benefits of pelleted feeds extend beyond mere nutrient availability. By improving gut health and reducing the impact of anti-nutritional factors, pelleted feeds contribute to enhanced overall health and well-being in broiler chickens [6]. Anti-nutritional factors, such as phytates and tannins, can inhibit nutrient absorption and negatively affect growth performance. However, pelleting can significantly reduce the levels of these factors, promote better nutrient utilization and minimizing health issues related to digestive disturbances [7].

Moreover, the importance of nutrient bioavailability in relation to broiler performance cannot be overstated. Improved nutrient absorption leads to better growth rates, enhanced feed conversion ratios, and superior meat quality. Nutrient-dense diets formulated with pelleted feeds can provide broilers with the essential vitamins, minerals, and amino acids needed for optimal growth and development [8]. This, in turn, supports the poultry industry's goal of producing high-quality meat that meets consumer demands.

Despite the known advantages of pelleted feeds, there remains a need for a comprehensive understanding of the underlying mechanisms that enhance nutrient bioavailability. This review aims to explore the intricate relationships between pelleted feed formulations and their impact on nutrient bioavailability, performance, health, and meat quality of broiler chickens. By synthesizing current research findings and highlighting the implications of these processes, this paper will contribute to the development of more effective feeding strategies in poultry production, ultimately advancing sustainability and food security in the sector.

This review presents a novel synthesis of mechanisms enhancing nutrient bioavailability in pelleted feeds and their implications for broiler chickens. By integrating insights from recent research, it identifies and elaborates on less-explored aspects of pelleting, such as the role of thermal and chemical modifications in optimizing gut health and reducing anti-nutritional factors. Furthermore, the review emphasizes the interconnectedness of nutrient absorption, performance metrics, and meat quality, providing a comprehensive framework for future feeding strategies. This approach aims to guide the poultry industry towards more sustainable practices, ultimately contributing to improved productivity and food security in an evolving market.

PHYSICAL CHANGES

Particle Size Reduction

The pelleting process involves grinding and compressing feed ingredients into smaller particles before forming pellets. The reduction in particle size enhances the bioavailability of nutrients by increasing the surface area of feed particles exposed to digestive enzymes [9]. Smaller particles are broken down more rapidly in the digestive tract, allowing for faster and more efficient digestion and nutrient absorption. This process also facilitates the passage of nutrients through the gastrointestinal system, minimizing nutrient loss to improve overall feed efficiency [10].

Pellet Uniformity

Pelleting results in more uniform feed pellets, ensuring each pellet contains a consistent ratio of nutrients. This uniformity minimizes the risk of nutrient imbalances or under-consumption of specific nutrients [11]. By providing consistent nutrient delivery, the bioavailability of critical dietary components is improved across all birds, ensuring that each animal receives an equivalent amount of the intended nutrients. Uniformity also reduces ingredient separation that often occurs with mash or loose feeds to maintain nutrient stability from the mill to the bird.

Nutrient Density

The pelleting process compresses the feed mixture, increasing the nutrient density per unit of feed. As a result, the same amount of feed delivers a higher concentration of nutrients, allowing the bird to

ingest the required levels of vitamins, minerals, proteins, and energy in a smaller volume of feed [8]. This not only promotes better nutrient intake but also enhances feed efficiency by allowing birds to meet their nutritional needs without having to consume excess bulk. High nutrient density is particularly important for broilers, which have fast growth rates.

Feed Palatability

Pelleting often enhances the palatability of feed, making it more appealing to poultry [12]. The heat and pressure applied during pelleting can improve the aroma and taste of the feed by altering its physical and chemical properties. Improved palatability encourages higher feed intake, which, in turn, ensures better nutrient intake and absorption. Additionally, the uniform and compact nature of pellets reduces feed sorting, ensuring that birds consume the complete nutrient profile in every bite, leading to more consistent performance.

Nutrient Exposure

The structural changes induced during pelleting, such as breaking down fibrous components or gelatinizing starch, increase the accessibility of nutrients to digestive enzymes in the gastrointestinal tract. This improved enzyme-substrate interaction allows enzymes to act more efficiently on feed components, promoting better breakdown and absorption of proteins, carbohydrates, and fats [5]. Enhanced enzymatic activity accelerates nutrient release and utilization in the small intestine where most of the digestion and absorption occur [13].

Micronutrient Homogeneity

Pelleting homogenizes feed ingredients, ensuring a uniform distribution of micronutrients, such as vitamins, minerals, and trace elements throughout each pellet [14]. This prevents uneven nutrient intake and promotes consistent nutrient availability for every bird. The compression of feed into pellets also protects sensitive micronutrients from segregation or degradation during storage and handling, which helps maintain their bioavailability and effectiveness.

Feed Density

Pelleted feed is denser than mash or crumbled feed, meaning more nutrients can be packed into each bite. This improved feed density is particularly beneficial for fast-growing broilers with high nutrient demands [15]. The dense structure of pellets reduces the physical space needed for digestion, promoting efficient gut fill without compromising nutrient absorption. It allows for easier handling, transportation, and storage of feeds.

Surface Area

Smaller, more uniform feed particles and the structural modifications caused by pelleting increase the surface area available for digestive enzymes to act upon [10]. This enhances the efficiency of nutrient digestion, as enzymes can more easily break down feed components into their absorbable forms. The increased enzymatic activity leads to quicker nutrient release and absorption, supporting faster growth and improved feed utilization.

Protein Pre-Softening

The heat and moisture applied during pelleting can cause partial denaturation or pre-softening of proteins, making them easier to digest [16]. Pre-softened proteins are more readily accessible to digestive enzymes, which can break them down more efficiently into peptides and amino acids for absorption. This enhances the bioavailability of essential amino acids, crucial for the rapid growth and muscle development seen in broiler chickens.

Starch Gelatinization

Pelleting induces the gelatinization of starches, particularly amylopectin, which becomes more soluble and digestible under heat and moisture. Gelatinized starch is broken down more easily by digestive enzymes like amylase, improving the availability of glucose for absorption [2]. This process

is particularly beneficial for energy metabolism in broilers, as the rapid availability of glucose supports their fast growth rates and energy-intensive physiological processes.

Particle Passage

Pelleted feed, with its smaller, more uniform particles, moves more efficiently through the digestive tract. The improved particle size distribution reduces retention time in the gizzard and facilitates faster gastric emptying. This allows for more rapid nutrient digestion and absorption in the small intestine, promoting faster growth and more efficient feed utilization [15]. It also reduces the risk of gut compaction to enhance overall gut health.

Feed Matrices

During pelleting, the compression of feed ingredients can form beneficial feed matrices that slow the release of certain nutrients, particularly starches and proteins [2]. These matrices can act as a controlled-release mechanism, allowing nutrients to be gradually broken down and absorbed over time. This sustained nutrient release ensures that the bird has a steady supply of energy and amino acids throughout the day, reducing the likelihood of nutrient surges and imbalances that could affect metabolism and growth.

Mechanical Breakdown

The mechanical action of grinding and compressing feed during pelleting results in the breakdown of tough, fibrous components of the feed, such as cellulose and hemicellulose [2]. This breakdown reduces the anti-nutritional effects of indigestible fiber, allowing for more efficient utilization of the nutrient-dense components of the feed. Improved feed breakdown enhances the bioavailability of nutrients trapped within fibrous matrices and supports better overall digestion and nutrient absorption in broilers.

THERMAL AND CHEMICAL EFFECTS

Starch Gelatinization

During pelleting, the application of heat and moisture causes starch, especially amylopectin, to undergo gelatinization. This process breaks down the crystalline structure of starch, making it more soluble and digestible [17–20]. Gelatinized starch is more accessible to digestive enzymes, such as amylase, improving the availability of glucose, which is a primary energy source for broilers. This enhanced starch digestibility promotes better energy utilization and supports the rapid growth and development of poultry.

Protein Denaturation

The heat and pressure during pelleting lead to the denaturation of proteins, altering their tertiary and quaternary structures. Denatured proteins become more digestible as they are more easily broken down by digestive enzymes like proteases [21, 22]. This results in an increased availability of essential amino acids, which are crucial for muscle development and overall growth in broilers. Denaturation also reduces the anti-nutritional effects of certain proteins that might otherwise hinder nutrient absorption.

Carbohydrate Breakdown

Pelleting breaks down complex carbohydrates into simpler sugars, enhancing their digestibility. The thermal treatment during pelleting disrupts the complex molecular structures of polysaccharides, converting them into more readily absorbable monosaccharides and oligosaccharides [23]. This conversion improves the energy supply to poultry and promotes faster growth, as simpler sugars are absorbed more efficiently in the small intestine, leading to better feed conversion and performance.

Ingredient Hydration

The steam and moisture introduced during pelleting hydrate feed ingredients, making them more malleable and easier to process [24]. This hydration improves the overall texture of the feed and

enhances the solubility of certain nutrients, making them more accessible to digestive enzymes. Hydration also helps in the formation of homogenous pellets, reducing the risk of ingredient separation and ensuring consistent nutrient intake.

Maillard Reaction

The pelleting process may lead to the formation of Maillard reaction products, which are created when reducing sugars interact with amino acids under high heat [2]. While some Maillard products can decrease the availability of certain amino acids, like lysine, they can also enhance the flavor and palatability of the feed. This improved taste encourages higher feed intake, promoting better nutrient consumption. However, it is important to control pelleting conditions to avoid excessive Maillard reactions, which can reduce the bioavailability of critical nutrients [25–27].

Reduction of Ingredient Separation

Pelleting helps reduce the separation of feed ingredients, particularly in mash feeds where particles of varying sizes tend to segregate during handling and transport [28]. The thermal and mechanical processing during pelleting binds ingredients together, ensuring that the nutrient composition of each pellet remains consistent. This uniformity reduces nutrient variability, ensuring that broilers consume a balanced diet with each bite, leading to more consistent growth and performance across the flock.

Cell Wall Breakdown

The application of heat and pressure during pelleting partially breaks down the cell walls of plant-based ingredients, making the nutrients more accessible to digestive enzymes [2, 29]. Plant cell walls, primarily composed of cellulose and lignin, are difficult for poultry to digest. Pelleting weakens these structures, allowing for better release and absorption of nutrients like carbohydrates, proteins, and lipids. This process is particularly beneficial for ingredients, like soy or cereal grains, that contain high levels of fiber.

Protein-Tannin Complex Breakdown

Tannins in plant-based feed ingredients can form complexes with proteins, reducing the digestibility of both. The heat generated during pelleting disrupts these protein-tannin complexes, freeing up the proteins and improving their availability for digestion [7]. By breaking these anti-nutritional complexes, the bioavailability of proteins increases, which is particularly important for fast-growing broilers for muscle development.

Hemicellulose Digestibility

Hemicellulose, a type of fiber found in plant cell walls, becomes more digestible after pelleting due to the heat treatment. The thermal processing partially breaks down the hemicellulose, making it easier for digestive enzymes to act upon [30]. Increased digestibility of hemicellulose enhances the absorption of nutrients, particularly energy, and reduces the anti-nutritional effects of indigestible fiber, contributing to improved feed efficiency.

Fiber Hydrolysis

The pelleting process induces partial hydrolysis of fibrous components in the feed, particularly cellulose and hemicellulose. This breakdown reduces the indigestible fiber content of the feed and makes it easier for the digestive system to extract nutrients from plant-based ingredients [31]. Partial fiber hydrolysis also decreases gut fill, allowing birds to consume more nutrient-dense feed and improving overall feed intake and efficiency.

Amylopectin Gelatinization

Like starch gelatinization, pelleting causes increased gelatinization of amylopectin, one of the two major components of starch. Gelatinized amylopectin is more soluble and easier to digest, providing a quick source of glucose for broilers [32]. This improved starch digestibility supports energy metabolism and leads to better growth rates, feed conversion ratios, and overall production performance.

Feed Pre-Digestion

Some feed components undergo partial pre-digestion during pelleting, especially proteins and carbohydrates [33]. The heat and moisture create conditions that mimic enzymatic activity, breaking down complex nutrients into simpler forms. This pre-digestion reduces the digestive workload for the bird and enhances nutrient absorption, leading to improved growth performance and nutrient utilization.

Increased Viscosity

Pelleting can increase the viscosity of digesta due to the gelatinization of starch and partial breakdown of fibrous components [34]. Increased digesta viscosity can slow down the passage of feed through the gastrointestinal tract, allowing more time for nutrient absorption [35]. However, excessive viscosity may sometimes impede digestion, so it is essential to balance the pelleting conditions to optimize nutrient bioavailability without negative effects on gut motility.

Cellulose Disintegration

The mechanical and thermal processing involved in pelleting causes partial disintegration of crystalline cellulose in plant-based ingredients [36]. Crystalline cellulose is a highly resistant form of fiber, and its breakdown during pelleting improves the availability of nutrients trapped within plant cell walls [31]. This process enhances the digestibility of plant-based ingredients and increases the bioavailability of both energy and protein.

Bioactive Peptide Formation

Pelleting may lead to the formation of bioactive peptides as proteins are denatured and partially hydrolyzed [2]. These peptides have various beneficial effects, including antimicrobial activity and improved gut health. By promoting the formation of bioactive peptides, pelleting enhances the overall health and performance of poultry, as these peptides can influence immune function and nutrient metabolism.

Nutrient Digestibility

Pelleting enhances nutrient digestibility, particularly at the ileal level, where most of the nutrient absorption takes place [22]. The thermal and chemical modifications to feed ingredients improve the breakdown and solubility of nutrients, making them more available for absorption in the small intestine. Increased digestibility at the ileal level ensures that essential nutrients, like amino acids, fatty acids, and glucose, are effectively absorbed, leading to better growth.

Feed Durability

Pelleting improves feed durability, ensuring that the physical integrity of pellets is maintained during storage, handling, and transport [37]. Durable pellets resist crumbling, minimizing nutrient loss and ingredient separation. This consistency helps maintain the nutrient content of feed throughout its shelf life, ensuring that broilers receive the intended nutrient profile with every feeding. Improved durability also reduces feed waste, enhancing overall feed efficiency.

INCREASED NUTRIENT ABSORPTION

Starch Gelatinization

The heat and moisture applied during pelleting result in starch gelatinization, breaking down the crystalline structure of starch and making it more soluble and digestible [38]. Gelatinized starch is more readily broken down by digestive enzymes like amylase, increasing the availability of glucose and other simple sugars [17]. This improved digestibility contributes to enhanced energy absorption, supporting broiler growth and efficient feed conversion. Starch gelatinization is particularly important for young birds, which have less developed digestive systems and benefit from more easily digestible carbohydrates.

Vitamin Solubility

Pelleting can increase the solubility of certain vitamins, particularly water-soluble ones like B-vitamins and vitamin C. The heat and pressure used in pelleting alter the physical properties of feed ingredients, improving the release and dispersion of vitamins within the digestive tract [39]. Increased solubility enhances the absorption of these essential micronutrients, which play crucial roles in metabolic functions, immune response, and overall health. By ensuring that these vitamins are more readily available for absorption, pelleting contributes to improved nutritional status and performance.

Fat Digestion

The pelleting process promotes the emulsification of fats, improving their digestibility. Emulsification breaks fat molecules into smaller droplets, increasing their surface area and making them more accessible to digestive enzymes like lipases [40]. Enhanced fat digestion leads to better absorption of fatty acids and fat-soluble vitamins (A, D, E, and K), which are crucial for energy metabolism, cell membrane integrity, and various physiological functions [41]. Improved fat digestion also supports better growth performance and feed efficiency in broilers.

Reduction of Trypsin Inhibitors

Pelleting reduces the levels of trypsin inhibitors present in certain feed ingredients, particularly in legumes like soybeans. Trypsin inhibitors interfere with the activity of digestive enzymes, particularly proteases, like trypsin, which are essential for protein digestion [2]. By inactivating these inhibitors, pelleting improves the digestibility and bioavailability of dietary proteins, allowing for more efficient amino acid absorption and better muscle development in broilers.

Absorption of Fat-Soluble Vitamin

The thermal treatment during pelleting enhances the absorption of fat-soluble vitamins (A, D, E, and K) by increasing the digestibility of fats, which act as carriers for these vitamins. The improved emulsification and digestion of fats during pelleting ensure that fat-soluble vitamins are more readily absorbed in the small intestine, where they are transported into the bloodstream for use in various metabolic processes [42]. Adequate absorption of these vitamins is crucial for bone health, immune function, and antioxidant defense.

Phytate Disruption

Pelleting disrupts the binding of phytates, which are anti-nutritional factors found in plant-based feed ingredients. Phytates bind to essential minerals, like calcium, zinc, and iron, making them unavailable for absorption. The heat and pressure involved in pelleting breaking these phytate-mineral complexes, freeing up the bound minerals and improving their bioavailability [43]. This enhances mineral absorption, supporting bone development, immune function, and overall growth performance in broilers.

Protein Solubility

The pelleting process increases protein solubility by denaturing proteins and making them more accessible to digestive enzymes [5]. Soluble proteins are more easily broken down into peptides and amino acids, which are essential for growth, muscle development, and other physiological functions in broilers. Improved protein solubility enhances the overall efficiency of nutrient utilization, ensuring that the bird's dietary protein requirements are met with less waste and better performance outcomes.

Lipid Digestion

Pelleting enhances lipid digestion by increasing the interaction between fats and digestive enzymes. The heat and pressure cause fats to emulsify, breaking them into smaller droplets that are more easily digested by lipases [44, 45]. Improved lipid digestion not only enhances the absorption of fatty acids but also supports the efficient utilization of fat-soluble vitamins. This process ensures that broilers receive the energy and nutrients they need for growth, immune function, and other critical processes.

Bile Salt Activity

Improved emulsification of fats during pelleting enhances the activity of bile salts, which are necessary for fat digestion. Bile salts facilitate the breakdown of fat droplets into smaller micelles, increasing the surface area available for lipase activity [46]. This leads to more efficient fat digestion and absorption, ensuring that the energy-rich components of the feed are utilized optimally. The enhanced function of bile salts also supports better absorption of fat-soluble vitamins and other lipid-based nutrients.

Mineral Absorption

Pelleting improves the absorption of trace minerals, like zinc and iron, by disrupting phytate complexes and increasing the availability of these minerals for absorption. Zinc and iron are essential for numerous physiological functions, including enzyme activity, immune response, and oxygen transport [47]. Improved mineral absorption ensures that broilers receive adequate levels of these critical nutrients, supporting optimal growth, immune health, and productivity.

Sodium-Potassium Balance

The pelleting process can improve the balance of sodium and potassium in feed, promoting better electrolyte balance in broilers. Sodium and potassium are critical for maintaining cellular homeostasis, nerve function, and muscle contraction [48]. By optimizing the bioavailability of these electrolytes, pelleting helps maintain proper hydration and supports metabolic efficiency, contributing to better performance and health in poultry [49].

Bioavailability of Energy Substrate

Pelleting increases the bioavailability of energy-rich substrates, such as carbohydrates and fats, which are essential for the rapid growth and high metabolic demands of broilers. By improving the digestibility and absorption of these substrates, pelleting ensures that broilers can convert feed into energy more efficiently [50]. This enhanced energy availability supports better feed conversion ratios, faster growth rates, and overall improved production performance.

Vitamin Release

Pelleting enhances the release of vitamins from plant-based ingredients, making them more accessible for absorption in the digestive tract. This is particularly important for vitamins that are bound within the cellular structures of plant ingredients, such as those in cereal grains or legumes. The thermal and mechanical effects of pelleting break down plant cell walls, releasing vitamins and other nutrients for more efficient absorption [2]. Improved vitamin release supports overall health, immune function, and growth in broilers.

ANTI-NUTRITIONAL FACTORS REDUCTION

Inactivation of Anti-Nutritional Factors

The heat and pressure applied during the pelleting process are highly effective at inactivating various anti-nutritional factors that can interfere with nutrient absorption [7]. These factors, which are commonly found in plant-based feed ingredients, can reduce the bioavailability of essential nutrients, such as proteins, vitamins, and minerals. Inactivation of these compounds enhances the overall nutritional value of the feed, ensuring better growth, health, and feed efficiency.

Trypsin Inhibitor Reduction

Trypsin inhibitors, present in many legume-based ingredients, such as soybeans, interfere with the activity of trypsin, an enzyme essential for protein digestion [51]. The heat treatment during pelleting significantly reduces the levels of these inhibitors, allowing for improved protein digestion and amino acid absorption [52]. By enhancing protein bioavailability, pelleting supports better muscle development, growth, and overall performance in broilers, especially when legume-based protein sources are used in feed formulations.

Mycotoxin Reduction

Mycotoxins, toxic compounds produced by certain fungi, can contaminate feed ingredients and pose serious risks to poultry health, leading to reduced growth performance, immune suppression, and organ damage [53]. Pelleting at high temperatures can reduce mycotoxin levels in feed by degrading these harmful compounds or altering their structure, rendering them less toxic [54, 55]. The reduction of mycotoxin levels during pelleting enhances feed safety and ensures that broilers are not exposed to these dangerous toxins, supporting better health and productivity.

Lipase Inhibitor Inactivation

Certain feed ingredients contain lipase inhibitors, which interfere with the activity of lipase, an enzyme responsible for breaking down fats [56]. Pelleting inactivates these inhibitors, allowing for better fat digestion and absorption. Improved lipid metabolism leads to better energy utilization, increased absorption of fat-soluble vitamins, and enhanced growth rates in broilers. By inactivating lipase inhibitors, pelleting maximizes the energy available from dietary fats, contributing to better feed efficiency.

Urease Activity Destruction

Urease, an enzyme found in some plant-based feed ingredients, like soybeans, can convert urea into ammonia, potentially leading to reduced feed palatability and lower nutrient absorption [57]. The heat generated during pelleting destroys urease activity, preventing the formation of ammonia and preserving feed quality [58]. This ensures that broilers consume feed with optimal protein content and no negative byproducts, contributing to improved feed conversion and growth performance.

Harmful Enzyme Inactivation

Various harmful enzymes present in raw feed ingredients can interfere with digestion and nutrient absorption. Pelleting inactivates these enzymes through thermal treatment, preventing them from degrading valuable nutrients or forming undesirable compounds [59]. The inactivation of harmful enzymes ensures that feed maintains its intended nutritional value, allowing broilers to digest and absorb nutrients more effectively.

Fiber-Mineral Bond Disruption

Certain fibers in plant-based feed ingredients can bind to essential minerals, like calcium, zinc, and iron, reducing their availability for absorption [60]. The heat and pressure during pelleting break these fiber-mineral bonds, freeing the minerals for better absorption in the digestive system. This enhances the bioavailability of important minerals, supporting bone development, immune function, and overall growth in broilers.

Pectin Inactivation

Pectin, a type of soluble fiber found in fruits and vegetables, can form gels in the digestive system and impede nutrient absorption [61]. The pelleting process inactivates pectin, reducing their gel-forming capacity and allowing for better nutrient digestion and absorption. By minimizing the anti-nutritional effects of pectin, pelleting improves feed efficiency and supports better growth and performance in broilers.

Pepsin Inhibitor Reduction

Pepsin inhibitors, which interfere with the activity of pepsin (a key enzyme in protein digestion), can be present in some plant-based feed ingredients. Pelleting reduces the levels of pepsin inhibitors, allowing for more effective protein breakdown in the stomach [62]. This leads to improved amino acid availability, better muscle development, and enhanced overall growth performance in broilers.

Tannin Inactivation

Tannins, found in some plant ingredients, can bind to proteins and other nutrients, reducing their digestibility [63]. The heat treatment during pelleting inactivates tannins, breaking the bonds, they form with proteins and making the nutrients more available for absorption [64]. This enhances the overall digestibility of the feed and ensures that broilers can effectively utilize dietary proteins, leading to better growth and productivity.

Thiaminase Inactivation

Thiaminase is an enzyme that can degrade thiamine (vitamin B1), an essential nutrient for energy metabolism and nervous system function [65]. Pelleting inactivates thiaminase, preserving the thiamine content in feed and ensuring that broilers receive adequate levels of this critical vitamin. Thiamine is important for growth, energy utilization, and overall health, and its preservation during pelleting supports optimal performance in broilers.

IMPROVED GUT HEALTH

Improved Gut Motility

Pelleted feed enhances gut motility by providing more uniform and easily digestible particles, which help stimulate the natural contractions of the gastrointestinal tract. This improves the movement of digesta through the gut, ensuring efficient mixing and better exposure of nutrients to digestive enzymes [4]. Improved gut motility not only enhances nutrient absorption but also reduces the risk of digestive disorders like constipation or impaction in broilers.

Better Enzyme-Substrate Interactions

Pelleting increases the availability of nutrients for digestive enzymes by breaking down feed particles and creating more accessible substrates [2]. This enhances enzyme-substrate interactions within the gut, improving the efficiency of nutrient breakdown and absorption. The closer interaction between enzymes and nutrients ensures that broilers can more effectively extract energy, amino acids, and other essential nutrients from their feed, leading to better growth and performance [66].

Reduction of Gut Irritation

Pelleting reduces gut irritation by producing feed with fewer sharp or abrasive particles. The more uniform and softer texture of pelleted feed minimizes physical damage to the intestinal lining, reducing the risk of inflammation and promoting a healthier gut environment [67]. Reduced gut irritation supports better nutrient absorption and overall digestive health, leading to improved feed conversion and growth rates in broilers.

Improved Gut Microflora

Pelleting can positively influence gut microflora by reducing the presence of anti-nutritional factors and providing a more consistent nutrient supply. A healthier gut environment encourages the growth of beneficial bacteria while limiting the proliferation of harmful microbes [68]. This balanced microbial population supports better digestion, enhances immune function, and reduces the risk of intestinal diseases, leading to improved overall health and performance in broilers [68].

Stabilization of Gut Hormone

Pelleted feed can help stabilize gut hormone signaling by providing a consistent and balanced nutrient supply, which in turn promotes optimal digestive function. Hormones, such as cholecystokinin (CCK) and gastrin regulate digestive processes, including enzyme secretion and gut motility [69]. Stabilized hormone signaling ensures that digestion proceeds efficiently, enhancing nutrient absorption and overall energy utilization, supporting optimal growth in broilers.

Increased Gut Transit Time

Pelleting may lead to a slight increase in gut transit time, allowing for more thorough digestion and nutrient absorption. The slower movement of feed through the digestive tract ensures that nutrients have more time to interact with digestive enzymes and be absorbed by the gut lining [66]. This extended digestion period improves the efficiency of nutrient extraction, supporting better growth and feed conversion in broilers.

Better Control over Gut Osmolarity

Pelleted feed improves control over gut osmolarity by ensuring a consistent nutrient and moisture balance in the digestive tract. Osmolarity affects the movement of water and electrolytes across the gut lining, influencing hydration, digestion, and nutrient absorption [70]. Better control over gut osmolarity helps maintain optimal digestive conditions, reducing the risk of diarrhea and promoting efficient nutrient uptake.

Improved Nutrient Extraction

Pelleting enhances the digestibility of fibrous feed ingredients by breaking down cell walls and making the nutrients within more accessible to digestive enzymes [71]. This improved nutrient extraction from fibrous materials allows broilers to utilize a wider range of feed ingredients, including those with higher fiber content. By maximizing the use of fibrous materials, pelleting supports more efficient nutrient absorption and overall growth performance.

Reduced Inflammatory Responses

Pelleting reduces feed-induced inflammatory responses by eliminating or reducing anti-nutritional factors and producing feed with fewer irritants. A less inflammatory gut environment improves overall gut health, enhances nutrient absorption, and reduces the energy costs associated with immune responses. This leads to better growth, efficiency, and overall health in broilers.

Reduced Ammonia Production

Pelleted feed reduces ammonia production in the gut by improving the digestion and absorption of proteins. Efficient protein digestion minimizes the amount of undigested protein that reaches the large intestine, where it would otherwise be fermented by bacteria, producing ammonia as a byproduct [72]. Reduced ammonia production helps maintain a healthier gut environment, supports better digestion, and reduces the risk of conditions like enteritis in broilers.

ENHANCED NUTRIENT UTILIZATION

Reduction of Feed Wastage

Pelleted feed significantly reduces feed wastage by providing a more compact, uniform form that is less prone to spillage and separation during handling and consumption [52]. Broilers can consume a greater proportion of the food offered, leading to more efficient nutrient intake and reducing the overall cost of production. This improvement in feed utilization ensures that the nutrients formulated into the feed are ingested and utilized by the birds, enhancing growth and performance.

Increased Release of Amino Acids

The pelleting process aids in breaking down the structural components of feed ingredients that can trap amino acids, making them more available for digestion and absorption. This release of bound amino acids improves protein quality and ensures that broilers have access to the essential amino acids needed for muscle growth, tissue repair, and overall metabolic function [73]. Enhanced amino acid availability contributes to better protein utilization and improved growth rates.

Reduction of Enzyme Inhibitors

Endogenous enzyme inhibitors, such as protease or amylase inhibitors, can hinder the digestive process by blocking the activity of key digestive enzymes. Pelleting helps to reduce or inactivate these

inhibitors, allowing for more effective digestion of proteins, starches, and other nutrients [2]. By neutralizing enzyme inhibitors, the pelleting process supports enhanced nutrient breakdown and absorption, leading to improved feed efficiency and broiler performance.

Improved Energy Utilization

Pelleting increases the energy utilization of feed by enhancing the digestibility of carbohydrates, fats, and proteins [2]. The heat and pressure involved in the pelleting process break down complex molecules into simpler, more digestible forms, allowing broilers to extract more energy from the feed. This improved energy utilization supports optimal growth, feed conversion, and overall health, maximizing the energy derived from the feed ingredients.

Increased Amino Acid Digestibility

Synthetic amino acids, often added to poultry diets to balance protein levels, are more efficiently digested when incorporated into pelleted feed [74]. The pelleting process ensures uniform distribution of synthetic amino acids throughout the feed and enhances their bioavailability. This increased digestibility of synthetic amino acids ensures that broilers receive the precise levels of these nutrients required for optimal growth, muscle development, and overall performance.

Reduction of Fiber Matrix

Fibrous feed ingredients can trap valuable nutrients, such as proteins, fats, and minerals, within their cell walls, making them less accessible for digestion [75]. Pelleting breaks down the fiber matrix, releasing these trapped nutrients and making them more available for absorption [31]. By reducing the anti-nutritive effects of fiber, pelleting ensures that broilers can better utilize the nutrients in high-fiber feed ingredients, improving overall nutrient availability and feed efficiency.

Improved Energy-Protein Balance

Pelleted feed improves the balance between protein and energy by ensuring more efficient digestion and absorption of both nutrients. Proper balance between protein and energy is critical for optimal growth, feed conversion, and metabolic health in broilers [76]. The pelleting process enhances the digestibility of both macronutrients, allowing broilers to more effectively utilize the energy and protein provided in their diet, leading to improved growth and performance.

Hydrolysis of Fiber

The pelleting process can partially hydrolyze fiber, breaking down its structure and reducing its anti-nutritive effects. This hydrolysis improves the digestibility of fiber-rich ingredients and allows for better absorption of the nutrients that are often trapped within fibrous cell walls [77]. By reducing the negative impact of fiber, pelleting enhances the overall utilization of feed components and supports better growth and feed conversion in broilers.

Improved Energy Balance

Pelleting promotes better overall energy balance in broiler diets by enhancing the digestibility of energy-rich feed ingredients, such as fats and carbohydrates [78]. This improved energy balance ensures that broilers receive adequate energy for growth, maintenance, and metabolic functions, leading to better feed efficiency and improved overall performance. A well-maintained energy balance is key to achieving optimal production outcomes in poultry farming.

REDUCTION OF NUTRIENT LOSS

Improved Fat Stability

Pelleting enhances the stability of fats in feed by preventing oxidation, which can lead to the deterioration of fat quality. The heat treatment during pelleting helps to eliminate free radicals and pathogens that can cause oxidative damage, ensuring that fats retain their nutritional value [79]. Improved fat stability contributes to better energy utilization and overall health in broilers by providing a reliable source of energy without compromising fat quality.

Reduced Nutrient Losses

The pelleting process minimizes nutrient losses by ensuring that essential vitamins, minerals, and other nutrients are preserved during heat application. Careful control of temperature and duration during pelleting prevents the degradation of sensitive nutrients, ensuring that the final product retains its nutritional integrity [2]. This reduction in nutrient loss maximizes the overall effectiveness of the feed, contributing to improved growth and feed conversion in broilers.

Reduced Nutrient Leaching

Pelleted feeds are less prone to nutrient leaching during storage compared to mash feeds. The pelleting process creates a more compact and stable product that is less susceptible to moisture absorption and subsequent nutrient loss [2]. By reducing leaching, pelleted feeds ensure that broilers receive the full complement of nutrients intended in their diets, leading to improved health and performance.

Reduced Feed Spoilage

Pelleted feeds are more resistant to spoilage due to their compact form and reduced moisture content. This lower susceptibility to spoilage results from the removal of excess moisture during pelleting, which inhibits the growth of mold and bacteria [80]. By minimizing feed spoilage, pelleted feeds maintain their quality over longer storage periods, ensuring that broilers receive safe and nutritious feed consistently.

Improved Fat Stability

The pelleting process helps improve the stability of fats in the feed, preventing rancidity, which occurs when fats undergo oxidative degradation. By reducing the exposure of fats to air and moisture, pelleting preserves their quality and extends their shelf life [79]. Maintaining fat stability is crucial for ensuring optimal digestion and absorption of fats by broilers, supporting their energy needs and overall health.

Reduced Oxidation of Fats

Pelleting reduces the oxidation of fats through a combination of heat treatment and improved packaging. The heat from pelleting inactivates enzymes and microorganisms that contribute to fat oxidation, while the compact structure of pellets limits oxygen exposure during storage [2]. This reduction in fat oxidation helps to preserve the nutritional value of the fats, ensuring that broilers receive high-quality energy sources in their diets.

Improved Fat Digestion

By preventing rancidity and maintaining the quality of fats, pelleted feeds ensure that oils remain digestible and usable by broilers. Rancid oils can lead to poor fat digestion and absorption, negatively impacting the birds' energy levels and overall health. The prevention of rancid oils in pelleted feeds promotes better fat digestion and contributes to more efficient nutrient utilization, enhancing growth performance.

PATHOGEN AND CONTAMINANT CONTROL

Inactivation of Pathogens

The pelleting process effectively inactivates a variety of pathogens, including bacteria and viruses, through the application of heat and pressure [81]. The elevated temperatures reached during pelleting help to eliminate harmful microorganisms, reducing the risk of disease transmission among poultry. By ensuring that feed is free from pathogens, pelleting contributes to improved health and productivity in broilers, decreasing the likelihood of gastrointestinal infections and associated health issues.

Reduction in Ingredient Toxicity

Pelleting can reduce ingredient toxicity, including harmful compounds, such as glycosides, through the application of heat during the processing stage. These toxic compounds can adversely affect the

health and performance of broilers. The high temperatures involved in pelleting help to break down or inactivate these toxins, making the feed safer for consumption [59]. This reduction in ingredient toxicity supports better growth rates and overall health in poultry.

Reduction of Heat-Labile Toxins

Pelleting is effective in reducing the levels of heat-labile toxins, such as aflatoxins, which are known to be harmful to poultry. The heat generated during pelleting can deactivate these toxins, rendering them less harmful and preventing their absorption in the gastrointestinal tract [82]. This process ensures that the feed remains safe and nutritious, supporting optimal growth and health in broilers while minimizing the risk of toxin-related disorders.

Inactivation of Mycotoxins

The pelleting process also inactivates mycotoxins, which are toxic metabolites produced by certain molds found in agricultural products. Mycotoxins can have detrimental effects on the health and performance of broilers, leading to decreased growth rates and increased susceptibility to disease [83]. The heat and pressure applied during pelleting effectively reduce the concentration of mycotoxins, ensuring that the feed is safer for poultry consumption and supporting better overall health and productivity.

IMPROVED NUTRIENT RETENTION

Stabilization of Micronutrients

The pelleting process helps stabilize vitamins and micronutrients in feed, protecting them from degradation caused by exposure to heat, moisture, and oxygen [39]. During pelleting, certain conditions can be controlled to ensure that sensitive nutrients, such as vitamins A, D, E, and certain B vitamins, remain intact. This stabilization is crucial for maintaining the nutritional quality of the feed, ensuring that broilers receive essential vitamins and minerals needed for optimal growth, immune function, and overall health.

Improved Nutrient Retention

Pelleted feeds exhibit improved nutrient retention during storage compared to unprocessed feeds. The pelleting process reduces the moisture content, which helps to prevent the growth of mold and the subsequent degradation of nutrients [2]. Additionally, the compact nature of pellets minimizes exposure to oxygen, reducing the risk of oxidation that can lead to nutrient loss. This enhanced nutrient retention ensures that broilers receive the full benefit of the formulated feed over extended storage periods, contributing to better growth performance and health.

Reduction of Nutrient Degradation

The durability of pellets plays a significant role in minimizing nutrient degradation. Well-formed pellets are less prone to breakage and dust generation, which can lead to the loss of nutrients and lower feed quality. The mechanical integrity of pelleted feed ensures that the nutrients remain encapsulated within the pellets until they are ingested by the birds [2]. This reduction in nutrient degradation during handling and feeding enhances the overall nutritional value of the feed and ensures that broilers can efficiently utilize the nutrients provided.

OPTIMIZATION OF EFFICIENCY

More Uniform Gastric Emptying

Pelleted feeds promote more uniform gastric emptying, which is crucial for optimizing digestion and nutrient absorption in broilers. The consistent size and density of pellets allow for a more controlled release of feed into the gastrointestinal tract, facilitating an even flow through the digestive system [84]. This uniformity minimizes fluctuations in gastric emptying rates, allowing for a steady nutrient supply to the intestines, where absorption occurs. Enhanced gastric emptying supports better digestion and nutrient utilization, contributing to improved growth rates and overall performance.

Reduced Feed Intake Time

The palatable nature of pelleted feeds encourages broilers to consume their meals more quickly, thereby reducing feed intake time. This efficiency in feeding allows for a greater amount of feed to be ingested in a shorter period, leading to enhanced digestion efficiency [85]. By minimizing the time spent eating, broilers can allocate more time to other important activities, such as resting and foraging, which can further improve their growth and well-being. Efficient feed intake promotes optimal growth rates and reduces feed costs per unit of weight gain.

Reduced Gut pH Variation

Pelleting helps to stabilize gut pH levels, promoting a more favorable environment for nutrient breakdown and absorption. The consistent nutrient profile of pelleted feed contributes to less fluctuation in gut pH, which can enhance the activity of digestive enzymes and microbial populations within the gut [9]. A stable pH facilitates optimal digestion of carbohydrates, proteins, and fats, leading to improved nutrient availability. This reduction in pH variation not only enhances feed efficiency but also supports overall gut health, reducing the risk of digestive disorders.

Improved Digestive Enzyme Secretion

The formulation of pelleted feeds can stimulate the secretion of digestive enzymes in broilers. The combination of heat treatment and the physical properties of pellets encourages the release of enzymes, such as amylase, protease, and lipase, which are essential for breaking down carbohydrates, proteins, and fats, respectively [86]. Increased enzyme secretion enhances the efficiency of nutrient digestion and absorption, maximizing the utilization of the feed provided. This improvement in digestive enzyme activity supports better growth performance and feed conversion ratios in broilers.

CONCLUSIONS

The enhancement of nutrient bioavailability in pelleted feeds represents a pivotal advancement in broiler chicken production. This review highlights the intricate mechanisms through which pelleting improves nutrient absorption, including physical alterations to feed structure, thermal and chemical transformations, and the mitigation of anti-nutritional factors. The implications of these improvements extend beyond nutrient efficiency; they encompass significant benefits for overall broiler performance, health, and meat quality. By optimizing pellet feed formulations, poultry producers can achieve better growth rates, feed conversion ratios, and meat quality, thereby meeting consumer demands for high-quality protein. Furthermore, the findings underscore the importance of gut health and digestive efficiency as critical components of successful feeding strategies. As the poultry industry faces ongoing challenges related to sustainability and food security, a comprehensive understanding of nutrient bioavailability in pelleted feeds will be essential for developing effective and sustainable feeding practices.

LIMITATIONS

First, the existing literature on pelleting techniques and their effects on nutrient bioavailability is still developing, and much of the research focuses on specific feed ingredients or narrow aspects of the pelleting process. This can lead to gaps in understanding the comprehensive interactions between various feed components and the overall nutritional dynamics in broiler chickens. Additionally, variations in the formulation of pelleted feeds, such as differences in ingredient quality, processing conditions, and manufacturing practices, can influence the outcomes observed in studies. These factors may limit the generalizability of findings across different poultry production systems and geographical regions.

Furthermore, while advancements in feed technology continue to emerge, there remains a need for standardized methods to assess nutrient bioavailability in practical settings. This inconsistency can complicate comparisons among studies and hinder the establishment of clear guidelines for optimizing pelleted feed formulations. Finally, the potential long-term effects of enhanced nutrient bioavailability

on broiler health and performance remain inadequately explored. Future research should address these limitations by investigating the cumulative impacts of pelleting on broiler chickens over extended periods and in various production environments. This will facilitate a deeper understanding of how optimized pelleted feeds can sustainably improve poultry production outcomes.

FUTURE DIRECTIONS

Future research on the enhanced bioavailability of nutrients in pelleted feeds for broiler chickens should focus on several key directions. Firstly, there is a need for comprehensive studies that investigate the interactions between different feed ingredients and their collective effects on nutrient bioavailability. This will help to elucidate the optimal combinations and processing conditions that maximize nutrient availability.

Secondly, further exploration of innovative pelleting technologies and techniques, such as the use of alternative heat sources, additives, or pre-treatment methods, could enhance the effectiveness of nutrient release and absorption. Research should also consider the impact of varying pellet sizes and densities on feeding behavior, digestion, and nutrient uptake.

Additionally, long-term studies are essential to assess the effects of pelleted feeds on overall broiler health, performance, and meat quality across different production systems and environmental conditions. This will provide insights into how enhanced nutrient bioavailability translates into practical benefits for poultry producers.

Moreover, investigating the potential of functional additives, such as probiotics, prebiotics, or enzymes, in conjunction with pelleted feeds could further improve gut health and nutrient utilization. Understanding the synergistic effects of these components will be crucial for developing more holistic feeding strategies.

Lastly, as consumer awareness of sustainability and animal welfare grows, future research should also focus on the environmental impact of optimized pelleted feeds and their role in promoting sustainable poultry production. This includes evaluating resource use efficiency, waste management, and the carbon footprint associated with various feeding strategies.

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