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The Role of Zinc in Animal Nutrition: Functions, Requirements, Sources, and Recent Advances

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ABSTRACT

Zinc is an essential trace mineral that plays a fundamental role in animal nutrition by supporting growth, metabolism, immune function, reproduction, and antioxidant defense. As a cofactor for numerous enzymes and regulatory proteins, zinc is involved in protein synthesis, cell division, gene expression, and tissue development. Adequate dietary zinc is necessary to maintain optimal health and productivity in livestock, poultry, aquaculture species, and companion animals, whereas deficiency can lead to impaired growth, reduced feed efficiency, weakened immunity, reproductive disorders, and increased susceptibility to diseases. Zinc is supplied through natural feed ingredients and dietary supplements in inorganic, organic, and nano forms, with bioavailability varying among sources. Recent advances in zinc nutrition have focused on improving mineral utilization through organic chelates and nanotechnology, thereby enhancing animal performance while reducing environmental zinc excretion. This review summarizes the biological functions, dietary requirements, sources, metabolism, and recent developments in zinc supplementation, highlighting its significance in sustainable and precision animal nutrition.

Keywords: Zinc; Animal nutrition; Trace mineral; Zinc bioavailability; Zinc supplementation; Immune function; Growth performance; Animal health.

1 INTRODUCTION

Zinc alloys, primarily brass, have been known from the beginning of recorded history. Zinc was produced as a free metal in India in the 13th Century. Marggraf, in 1746, labeled zinc as an element by reducing calamine in Europe. Establishing zinc as an essential element is credited to Todd et al. (1934) using a rat model. Their diet model was a chemically deficient diet and so little zinc was required to correct the deficiency that for many years a deficiency, by consuming natural foodstuffs, was not considered possible. There is a striking difference in dietary considerations between monogastric animals and ruminants. Monogastric animals tend to consume more seeds or seed-based food products that contain phytate whereas ruminants are grazing animals and derive a greater portion of their energy from grasses and leaf-bearing legumes. This changes the nutritional aspects considerably. Ruminants with a functioning rumen that depends more on bacteria and protozoa for converting roughages to energy must be considered separately. Rumen microorganisms may also contain active phytases.

Young nursing ruminant animals that have not developed a functioning rumen are essentially monogastric animals. In calves this is about the first 30 days of life. It is a common practice in the USA for large milking operations to nurse calves for about 3-4 days, the period of time for colostrum to be secreted. The cow is then transferred to the milking herd and the calves are given a synthetic formula until they can consume and utilize forage. Some commercial calf formulae are whey-based and provide satisfactory performance while others are soybean protein-based and because of an induced zinc deficiency thus will provide less than optimum performance, unless adequately fortified.

The importance of zinc in animal nutrition has received increasing attention due to its direct influence on growth performance, feed efficiency, disease resistance, reproductive efficiency, and product quality in livestock, poultry, aquaculture species, and companion animals. Zinc deficiency, resulting from inadequate dietary intake, poor bioavailability, or interactions with other dietary components, can impair growth, reduce feed intake, weaken immune responses, delay wound healing, and increase susceptibility to infectious diseases. Conversely, excessive zinc supplementation may interfere with the absorption of other essential minerals and contribute to environmental pollution through increased mineral excretion.

Zinc is supplied to animals through natural feed ingredients and mineral supplements, which are available in inorganic, organic, and more recently, nano forms. Advances in animal nutrition have focused on improving zinc bioavailability and utilization by developing highly absorbable zinc sources that enhance animal performance while minimizing environmental impacts. Organic zinc complexes and nanotechnology-based zinc supplements have shown considerable promise in improving mineral absorption, immune function, antioxidant status, and overall productivity.

2. IMPORTANCE OF ZINC IN ANIMAL NUTRITION

Zinc (Zn) acts as a catalytic, structural, and regulatory component of numerous enzymes, transcription factors, and proteins, making it one of the most important micronutrients in animal nutrition.

One of the primary functions of zinc is its involvement in enzyme activity. More than 300 enzymes require zinc as a cofactor for catalyzing reactions related to carbohydrate, protein, lipid, and nucleic acid metabolism. These enzymes regulate digestion, nutrient utilization, energy production, and cellular metabolism, thereby supporting efficient growth and maintenance of body tissues.

Zinc is also essential for growth and tissue development. It plays a key role in DNA and RNA synthesis, protein synthesis, cell proliferation, and differentiation, all of which are critical during periods of rapid growth, pregnancy, lactation, and tissue repair. Adequate zinc nutrition promotes skeletal development, muscle growth, and proper organ function in livestock, poultry, and aquaculture species.

The immune system is highly dependent on sufficient zinc availability. Zinc supports both innate and adaptive immunity by regulating the development and function of immune cells, including neutrophils, macrophages, natural killer cells, T lymphocytes, and B lymphocytes. It also enhances antibody production, cytokine regulation, and resistance to infectious diseases. Animals receiving adequate zinc generally exhibit improved immune competence and reduced disease incidence.

Another important function of zinc is its contribution to antioxidant defense. Zinc is an essential component of the antioxidant enzyme copper-zinc superoxide dismutase (Cu/Zn-SOD), which protects cells from oxidative damage caused by reactive oxygen species. By maintaining cellular integrity and reducing oxidative stress, zinc supports overall health, improves stress tolerance, and enhances recovery from disease or environmental challenges.

Zinc also plays a significant role in reproduction and fertility. It is involved in hormone synthesis, spermatogenesis, ovarian function, embryonic development, and fetal growth. Adequate zinc nutrition improves reproductive performance by enhancing conception rates, embryo viability, semen quality, and offspring development. Deficiency can result in delayed sexual maturity, impaired fertility, embryonic loss, and poor reproductive efficiency.

In addition, zinc contributes to maintaining the integrity of the skin, hooves, feathers, wool, and mucosal tissues. It is essential for collagen synthesis, keratin formation, and wound healing. Adequate zinc intake helps prevent skin disorders, foot lesions, feather abnormalities, and poor coat quality while promoting faster tissue repair following injury or infection.

3. SOURCES AND DIETARY REQUIREMENTS OF ZINC

Zinc is supplied to animals through both natural feed ingredients and dietary mineral supplements. Because the zinc content and bioavailability of feeds vary considerably, careful diet formulation is essential to meet the nutritional requirements of different animal species and production stages. Adequate zinc intake is necessary to support growth, reproduction, immune function, enzyme activity, and overall productivity while preventing deficiency disorders.

3.1 Natural Sources of Zinc

Natural feed ingredients differ widely in their zinc concentration and availability. Animal-derived feedstuffs generally contain more highly bioavailable zinc than plant-based ingredients because they are less affected by antinutritional factors. Rich natural sources include meat meal, fish meal, poultry by-product meal, milk products, and eggs. Among plant sources, oilseed meals, cereal grains, legumes, and forages contribute varying amounts of dietary zinc. However, the bioavailability of zinc from plant ingredients is often reduced by phytate, dietary fiber, and high concentrations of calcium or other minerals that form insoluble complexes with zinc in the gastrointestinal tract. Consequently, animals consuming diets based primarily on cereals and legumes may require supplemental zinc to meet their nutritional needs.

3.2 Zinc Supplements

To ensure adequate zinc intake, commercial animal diets are commonly fortified with mineral supplements. Inorganic zinc sources, such as zinc sulfate ($ZnSO_4$), zinc oxide (ZnO), zinc chloride ($ZnCl_2$), and zinc carbonate ($ZnCO_3$), are widely used because of their availability and relatively low cost. Among these, zinc sulfate generally exhibits higher solubility and bioavailability than zinc oxide.

Organic zinc sources, including zinc methionine, zinc lysine, zinc proteinate, zinc amino acid complexes, and zinc glycinate, have gained increasing attention because they often demonstrate greater bioavailability and absorption efficiency. Organic forms are less susceptible to interactions with dietary antagonists and may improve growth performance, immune function, reproductive efficiency, and antioxidant status while reducing zinc excretion into the environment.

Recent developments in animal nutrition have also introduced nano zinc oxide (nano-ZnO) as a promising alternative. Due to its extremely small particle size and large surface area, nano zinc exhibits enhanced absorption and biological activity compared with conventional zinc sources. Studies suggest that nano zinc can improve feed efficiency, immune response, antioxidant capacity, and intestinal health at lower supplementation levels, although further research is needed to establish its long-term safety and optimal inclusion rates.

3.3 Dietary Requirements of Zinc

The dietary requirement for zinc varies according to species, breed, age, physiological status, production level, health condition, and the bioavailability of dietary zinc. Growing animals, pregnant and lactating females, and high-producing livestock generally require higher zinc concentrations than mature animals at maintenance.

Nutrient requirement guidelines published by organizations such as the National Research Council (NRC) and other international authorities provide recommended dietary zinc concentrations for different animal species. Typical dietary requirements are approximately 30–60 mg/kg of diet for cattle and sheep, 40–60 mg/kg for swine, 40–80 mg/kg for poultry, and 15–100 mg/kg for most aquaculture species, depending on species and production stage. Companion animals such as dogs and cats also require adequate dietary zinc to support growth, skin integrity, immune function, and reproduction.

Several factors influence the actual zinc requirement of animals. These include dietary phytate concentration, calcium levels, interactions with copper and iron, feed processing methods, environmental stress, disease challenges, and the chemical form of zinc used in the diet. Diets containing high levels of phytate or calcium may reduce zinc absorption, thereby increasing the need for supplementation. Likewise, periods of rapid growth, heat stress, infection, and reproduction often increase zinc requirements due to greater metabolic demand.

4 PHYSIOLOGICAL FUNCTIONS OF ZINC

Zinc (Zn) is an essential trace mineral that performs numerous physiological functions in animals through its catalytic, structural, and regulatory roles. It is involved in a wide range of biochemical processes that are fundamental to growth, metabolism, immunity, reproduction, antioxidant defense, and tissue integrity.

4.1 Enzyme Activation and Metabolism

One of the primary physiological functions of zinc is its role as a cofactor for numerous enzymes involved in carbohydrate, protein, lipid, and nucleic acid metabolism. Zinc-dependent enzymes, including carbonic anhydrase, alkaline phosphatase, alcohol dehydrogenase, RNA polymerase, and DNA polymerase, participate in digestion, nutrient utilization, energy production, acid–base balance, and cellular metabolism. By regulating enzyme activity, zinc supports efficient nutrient conversion and normal physiological function.

4.2 Protein Synthesis and Gene Expression

Zinc is essential for protein synthesis, DNA replication, RNA transcription, and cell division. It stabilizes the structure of zinc-finger proteins, which are transcription factors that regulate the expression of numerous genes involved in growth, development, metabolism, and immune responses. Through these mechanisms, zinc influences cellular differentiation, tissue growth, and repair.

4.3 Growth and Development

Adequate zinc nutrition is indispensable for normal growth and skeletal development. Zinc promotes cell proliferation, bone formation, muscle development, and organ growth by supporting nucleic acid and protein synthesis. It is particularly important during periods of rapid growth, including early life, pregnancy, lactation, and post-weaning. Zinc deficiency during these stages may result in reduced growth rate, poor feed conversion efficiency, delayed skeletal maturation, and impaired tissue development.

4.4 Immune Function

Zinc plays a central role in maintaining both innate and adaptive immune responses. It regulates the development, maturation, and activity of immune cells such as neutrophils, macrophages, natural killer cells, T lymphocytes, and B lymphocytes. Zinc also influences cytokine production, antibody synthesis, and inflammatory responses. Adequate zinc status enhances disease resistance, improves vaccine responses, and reduces susceptibility to bacterial, viral, and parasitic infections. Conversely, zinc deficiency suppresses immune function and increases the risk of infectious diseases.

4.5 Antioxidant Defense

Zinc contributes significantly to antioxidant protection by serving as an essential component of the enzyme copper-zinc superoxide dismutase (Cu/Zn-SOD), which neutralizes reactive oxygen species and minimizes oxidative stress. Zinc also stabilizes cell membranes, protects proteins and DNA from oxidative damage, and helps preserve cellular integrity during environmental and metabolic stress. Improved antioxidant status supports better health, productivity, and resilience under challenging production conditions.

4.5 Reproductive Performance

Zinc is essential for normal reproductive function in both male and female animals. In males, it is involved in testicular development, spermatogenesis, testosterone synthesis, and sperm motility. In females, zinc supports ovarian function, follicular development, hormone production, fertilization, embryonic development, and fetal growth. Adequate zinc intake improves fertility, conception rate, reproductive efficiency, and offspring viability, whereas deficiency can lead to infertility, delayed sexual maturity, embryonic mortality, and poor neonatal development.

4.6 Skin Integrity and Wound Healing

Zinc is required for collagen synthesis, epithelial cell proliferation, keratin formation, and tissue repair. It helps maintain the integrity of the skin, hooves, claws, feathers, wool, and mucosal surfaces while accelerating wound healing and reducing the incidence of skin lesions. Zinc deficiency is commonly associated with dermatitis, parakeratosis, poor feathering, hoof abnormalities, impaired wound healing, and reduced resistance to skin infections.

4.7 Nervous System and Hormonal Regulation

Zinc plays an important role in nervous system development and function by participating in neurotransmitter synthesis, synaptic signaling, and neuronal communication. It also influences endocrine function by regulating the synthesis, storage, and secretion of several hormones, including insulin, growth hormone, thyroid hormones, and reproductive hormones. These actions contribute to normal metabolism, growth, appetite regulation, and physiological homeostasis.

4.8 Gastrointestinal Health

Adequate zinc nutrition supports gastrointestinal integrity by maintaining the structure and function of the intestinal epithelium. Zinc promotes intestinal cell regeneration, strengthens tight junctions between epithelial cells, and improves nutrient absorption. It also enhances gut immune function and helps reduce intestinal inflammation, contributing to better feed efficiency and overall digestive health, particularly in young and newly weaned animals.

5. ZINC AND ANIMAL HEALTH

Zinc (Zn) is a vital trace mineral that plays a central role in maintaining animal health by supporting immune function, antioxidant defense, tissue integrity, metabolic regulation, and resistance to environmental and pathogenic stress. Because zinc is involved in numerous physiological and biochemical processes, adequate dietary intake is essential for preventing disease and promoting overall health and welfare in livestock, poultry, aquaculture species, and companion animals.

5.1 Zinc and Immune Competence

Zinc is essential for the normal development and function of both innate and adaptive immune systems.

It regulates the proliferation, differentiation, and activity of immune cells, including neutrophils, macrophages, dendritic cells, natural killer cells, T lymphocytes, and B lymphocytes. Zinc also influences cytokine production, antibody synthesis, and inflammatory responses, thereby enhancing the animal's ability to combat bacterial, viral, fungal, and parasitic infections. Adequate zinc nutrition has been associated with improved vaccine responses, reduced disease incidence, and faster recovery from infections, whereas zinc deficiency impairs immune competence and increases susceptibility to disease.

5.2 Antioxidant Protection and Stress Resistance

Oxidative stress is a major factor affecting animal health, particularly during periods of rapid growth, disease, heat stress, transportation, weaning, and high production. Zinc contributes to antioxidant defense by serving as a structural component of copper-zinc superoxide dismutase (Cu/Zn-SOD), an enzyme that neutralizes reactive oxygen species and protects cells from oxidative damage. In addition, zinc stabilizes cell membranes, reduces lipid peroxidation, and helps preserve the integrity of proteins and nucleic acids. These antioxidant functions improve the animal's ability to tolerate environmental and metabolic stress, thereby enhancing health and productivity.

5.3 Gastrointestinal Health

Zinc plays an important role in maintaining the structure and function of the gastrointestinal tract. It supports intestinal epithelial cell proliferation, strengthens tight junction proteins, and promotes the repair of damaged intestinal tissues. Adequate zinc nutrition improves nutrient digestion and absorption while reducing intestinal permeability and inflammation. In young animals, particularly weaned piglets and poultry, zinc supplementation has been shown to reduce the incidence of diarrhea, improve gut health, and enhance growth performance by supporting intestinal integrity and microbial balance.

5.4 Skin, Hoof, and Tissue Integrity

Zinc is essential for maintaining healthy skin, hair, wool, feathers, hooves, and mucosal tissues. It participates in collagen synthesis, keratin formation, epithelial cell differentiation, and wound healing. Animals receiving adequate zinc exhibit healthier skin and stronger hooves, while deficiency may result in parakeratosis, dermatitis, alopecia, feather abnormalities, hoof lesions, delayed wound healing, and increased susceptibility to secondary infections. Proper zinc nutrition therefore contributes significantly to animal welfare and longevity.

5.5 Reproductive Health

Zinc is required for normal reproductive performance in both males and females. In males, it supports spermatogenesis, sperm maturation, testosterone production, and semen quality. In females, zinc contributes to ovarian function, hormone synthesis, fertilization, embryonic implantation, fetal development, and successful parturition. Adequate zinc intake improves fertility, conception rates, embryo survival, and offspring viability, whereas deficiency can impair reproductive efficiency and increase embryonic losses.

5.6 Disease Prevention and Recovery

Adequate zinc nutrition enhances the animal's natural defense mechanisms and supports recovery following disease or injury. Zinc regulates inflammatory responses, promotes tissue regeneration, accelerates wound healing, and facilitates the repair of damaged epithelial surfaces. It also helps maintain normal appetite during illness and supports metabolic processes required for recovery. Consequently, zinc supplementation is frequently incorporated into nutritional strategies designed to reduce disease-related economic losses and improve animal resilience.

5.7 Health Consequences of Zinc Deficiency

Insufficient dietary zinc can have widespread effects on animal health. Clinical signs of deficiency include reduced feed intake, poor growth, weakened immune responses, increased disease susceptibility, skin lesions, delayed wound healing, impaired reproduction, skeletal abnormalities, and reduced productivity. The severity of deficiency depends on the duration of inadequate intake, dietary antagonists such as phytate, and the physiological status of the animal. Early diagnosis and appropriate zinc supplementation are therefore essential to prevent long-term health and economic losses.

6 ZINC AND ANIMAL PRODUCTIVITY

Zinc (Zn) is an essential trace mineral that significantly influences animal productivity by supporting growth, feed utilization, reproductive performance, product quality, and overall production efficiency. Adequate zinc nutrition enables animals to achieve their genetic potential for production while improving health and resilience under diverse management and environmental conditions.

6.1 Growth Performance

One of the most important contributions of zinc to animal productivity is its effect on growth performance. Zinc is essential for DNA and RNA synthesis, protein metabolism, cell proliferation, and tissue development, all of which are critical for normal growth. Adequate zinc supplementation has consistently been associated with increased body weight gain, improved average daily gain, and enhanced skeletal and muscle development in livestock, poultry, and aquaculture species. Young and rapidly growing animals are particularly responsive to adequate dietary zinc because of their high metabolic demands.

6.2 Feed Intake and Feed Conversion Efficiency

Zinc improves feed utilization by promoting appetite, maintaining gastrointestinal health, and enhancing the activity of digestive enzymes involved in nutrient digestion and absorption. It supports intestinal epithelial integrity, increases nutrient bioavailability, and improves digestive efficiency. Consequently, animals receiving adequate zinc often exhibit higher feed intake and better feed conversion ratio (FCR), allowing more efficient conversion of feed into body weight or animal products.

6.3 Milk Production and Dairy Performance

In dairy animals, zinc plays a vital role in maintaining udder health, metabolic function, and milk production. Adequate zinc nutrition supports mammary gland development, enhances immune function, and reduces the incidence of mastitis by strengthening the integrity of the teat canal and improving resistance to bacterial infections. Organic zinc supplementation has been associated with improved milk yield, better milk composition, lower somatic cell counts, and enhanced reproductive performance in dairy cattle and small ruminants.

6.4 Egg Production and Poultry Performance

In poultry, zinc is essential for optimal growth, feather development, skeletal integrity, and egg production. Dietary zinc supplementation improves egg production rate, egg weight, eggshell thickness, shell strength, and hatchability. It also enhances embryo development and chick viability by supporting normal reproductive physiology and antioxidant defense. In broiler chickens, adequate zinc nutrition improves body weight gain, carcass yield, feed efficiency, and resistance to environmental and infectious stress.

6.5 Meat Quality

Zinc contributes to improved meat quality by promoting muscle development, protein synthesis, and antioxidant protection. Adequate zinc reduces oxidative damage in muscle tissues, thereby improving meat color, tenderness, water-holding capacity, and shelf life. Enhanced immune function and reduced physiological stress also contribute to healthier animals and superior carcass characteristics. In addition, zinc supplementation may reduce the occurrence of production-related disorders that negatively affect carcass quality.

6.6 Reproductive Performance

Efficient reproduction is essential for sustainable animal production, and zinc plays a key role in reproductive success. In breeding males, zinc improves testicular development, sperm production, sperm motility, and semen quality. In females, it supports ovarian function, hormone synthesis, conception, embryo survival, fetal growth, and successful parturition. Improved reproductive efficiency results in higher conception rates, shorter calving or lambing intervals, increased litter size in some species, and greater offspring survival, all of which enhance overall farm productivity.

6.7 Disease Resistance and Production Efficiency

Zinc strengthens immune function, reduces oxidative stress, and improves resistance to infectious diseases, thereby minimizing production losses associated with illness. Healthier animals require fewer therapeutic interventions, exhibit lower mortality rates, and maintain consistent growth and production performance. The ability of zinc to enhance disease resistance is particularly valuable under intensive production systems where animals are exposed to greater environmental and management-related challenges.

6.8 Productivity under Stress Conditions

Livestock frequently experience stress due to heat, transportation, weaning, overcrowding, dietary changes, and disease exposure. These stressors reduce feed intake, impair metabolism, and suppress productivity. Zinc supplementation enhances antioxidant capacity, stabilizes cellular membranes, supports endocrine function, and maintains intestinal integrity, enabling animals to better tolerate stress. Consequently, zinc helps sustain growth, reproduction, and production performance during periods of environmental or physiological stress.

6.9 Role of Novel Zinc Sources in Productivity

Recent advances in animal nutrition have focused on improving zinc utilization through organic zinc complexes and nano-zinc supplements. Compared with conventional inorganic zinc sources, these newer forms generally exhibit greater bioavailability, resulting in improved nutrient absorption, enhanced growth performance, stronger immune responses, better reproductive outcomes, and reduced mineral excretion. Their use supports precision nutrition by improving production efficiency while minimizing environmental contamination from excess dietary zinc.

7. ZINC DEFICIENCY AND TOXICITY

Maintaining an adequate zinc (Zn) balance is essential for optimal animal health, welfare, and productivity. Both zinc deficiency and excessive zinc intake can adversely affect physiological functions, growth, reproduction, immune competence, and metabolic processes. Therefore, understanding the causes, clinical manifestations, and consequences of zinc imbalance is crucial for developing effective nutritional management strategies in animal production.

7.1 Zinc Deficiency

Zinc deficiency is one of the most common trace mineral deficiencies in animals and may occur when dietary zinc intake is inadequate, zinc bioavailability is reduced, or the animal's physiological requirements exceed dietary supply. Deficiency may be classified as primary, resulting from insufficient dietary zinc, or secondary, resulting from impaired absorption due to interactions with other dietary components such as phytate, excessive calcium, iron, or copper.

Growing animals, pregnant and lactating females, and high-producing livestock are particularly susceptible to zinc deficiency because of their increased metabolic demands. Diets based predominantly on cereal grains and plant protein sources are also more likely to induce zinc deficiency due to the high phytate content, which binds zinc and reduces its intestinal absorption.

7.2 Clinical Signs of Zinc Deficiency

The clinical manifestations of zinc deficiency vary among animal species but generally reflect zinc's involvement in growth, immunity, reproduction, and tissue maintenance. Common signs include:

- Reduced feed intake and poor appetite.
- Decreased growth rate and poor feed conversion efficiency.
- Impaired skeletal development and delayed maturation.
- Skin lesions, dermatitis, parakeratosis, alopecia, and poor feathering or wool quality.
- Delayed wound healing and impaired tissue repair.
- Reduced immune function and increased susceptibility to infectious diseases.
- Reproductive disorders, including delayed puberty, reduced fertility, poor semen quality, embryonic mortality, and decreased offspring viability.
- Increased oxidative stress and reduced antioxidant capacity.
- Lower milk production, egg production, and overall productive performance.

In severe or prolonged cases, zinc deficiency can lead to significant economic losses due to reduced productivity, increased veterinary costs, poor reproductive performance, and higher mortality.

7.3 Zinc Toxicity

Although zinc is an essential nutrient, excessive dietary supplementation may result in toxicity. Zinc toxicity generally occurs when animals consume diets containing zinc concentrations well above their physiological requirements for extended periods. Accidental over-supplementation, industrial contamination, excessive use of mineral premixes, or ingestion of zinc-containing materials may also contribute to toxicity.

Compared with deficiency, zinc toxicity is relatively uncommon under normal feeding conditions because homeostatic mechanisms regulate zinc absorption and excretion. However, excessive zinc intake can disrupt mineral balance and interfere with the metabolism of other essential trace elements, particularly copper and iron.

7.4 Clinical Signs of Zinc Toxicity

The severity of zinc toxicity depends on the dose, duration of exposure, species, age, and nutritional status of the animal. Common clinical signs include:

- Reduced feed intake and poor growth performance.
- Gastrointestinal irritation, including vomiting, diarrhea, and reduced nutrient absorption.
- Depression, lethargy, and decreased productivity.
- Impaired immune function under chronic excessive intake.
- Copper deficiency due to antagonistic interactions, leading to anemia, reduced pigmentation, poor wool or hair quality, and impaired growth.
- Altered liver and kidney function in severe cases.

- Disturbances in mineral metabolism and enzyme activity.

Chronic excessive zinc supplementation may also increase zinc excretion in manure, contributing to soil accumulation and environmental contamination, particularly in intensive livestock production systems.

7.5 Prevention and Nutritional Management

Preventing zinc imbalance requires careful diet formulation based on species-specific nutrient requirements and the bioavailability of dietary zinc sources. Regular evaluation of feed composition, use of balanced mineral premixes, and adherence to established nutritional guidelines help ensure adequate zinc intake without excessive supplementation.

The use of highly bioavailable organic zinc sources and precision feeding strategies can improve zinc utilization while reducing dietary inclusion levels and environmental losses. Feed additives such as phytase can enhance zinc absorption by degrading phytate in plant-based diets, thereby reducing the need for high supplementation rates.

Monitoring animal performance, clinical signs, and, where appropriate, laboratory indicators such as serum or plasma zinc concentrations can assist in the early detection of zinc deficiency or excess. Prompt nutritional intervention minimizes production losses and supports long-term animal health and welfare.

8. FACTORS INFLUENCING ZINC BIOAVAILABILITY

Zinc bioavailability is influenced by a complex interaction of dietary composition, chemical form, physiological status, feed processing methods, and environmental conditions. Strategies such as using highly bioavailable zinc sources, reducing dietary phytate levels, and supplementing phytase enzymes can significantly enhance zinc utilization. Optimizing these factors is essential for improving animal performance, health, and sustainability in modern production systems.

8.1 Dietary Factors

Phytate Content: One of the most important dietary inhibitors of zinc absorption is phytate (phytic acid), which is abundant in cereal grains, legumes, and oilseed meals. Phytate forms insoluble complexes with zinc in the gastrointestinal tract, reducing its solubility and absorption. Diets high in phytate, particularly in non-ruminant animals such as poultry and swine, significantly decrease zinc bioavailability.

Calcium and Other Minerals: High dietary calcium levels can further reduce zinc absorption by forming insoluble complexes with phytate and zinc. Similarly, excessive levels of iron and copper may compete with zinc for absorption sites in the intestine, leading to reduced zinc uptake when dietary balance is not maintained.

Protein Source and Dietary Composition: Animal-based protein sources generally enhance zinc bioavailability compared to plant-based ingredients due to lower phytate content and better digestibility. Diets rich in fiber may also reduce zinc absorption by accelerating intestinal transit time and binding minerals within the gut.

Zinc Source and Chemical Form: The chemical form of dietary zinc strongly influences its absorption efficiency. Inorganic zinc sources such as zinc oxide and zinc sulfate differ in solubility, with zinc sulfate typically exhibiting higher bioavailability. Organic zinc sources, including zinc amino acid complexes, zinc proteinate, and zinc chelates, are generally more bioavailable due to improved stability and reduced interaction with dietary antagonists. Recent advances in nanotechnology have introduced nano-zinc, which possesses a higher surface area and enhanced absorption potential. However, long-term safety and optimal dosage levels of nano-zinc still require further investigation.

8.2 Physiological Factors

Species and Age: Zinc requirements and absorption efficiency vary among species and age groups. Young, growing animals typically have higher zinc absorption efficiency due to increased metabolic demands, whereas older animals may show reduced absorption capacity.

Health and Gut Integrity: Gastrointestinal health significantly affects zinc absorption. Intestinal diseases, inflammation, or damage to the mucosal lining can impair zinc uptake. Conversely, a healthy gut with intact epithelial cells promotes efficient mineral absorption.

Endogenous Zinc Regulation: Animals possess homeostatic mechanisms that regulate zinc absorption and excretion. When dietary zinc intake is high, absorption decreases and excretion increases, whereas zinc absorption is enhanced during deficiency states.

8.3 Nutritional and Management Factors

Feed Processing: Feed processing techniques such as heat treatment, pelleting, and fermentation can influence zinc availability. Some processes may reduce phytate content and improve zinc absorption, while excessive heat may alter mineral stability.

Enzyme Supplementation: The use of exogenous enzymes, particularly phytase, significantly improves zinc bioavailability by hydrolyzing phytate complexes in plant-based diets. This increases free zinc ions available for absorption and reduces the need for high dietary supplementation.

Interaction with Vitamins: Certain vitamins, especially vitamin D, may influence zinc metabolism by improving intestinal absorption and utilization. Adequate vitamin status supports optimal mineral balance and metabolic efficiency.

8.4 Environmental and Stress Factors

Environmental stressors such as heat stress, transportation, disease challenges, and high production demands can increase zinc requirements and affect its utilization. Under such conditions, even adequate dietary zinc levels may become insufficient due to increased metabolic turnover and oxidative stress.

9. RECENT ADVANCES IN ZINC SUPPLEMENTATION

Recent developments in animal nutrition have significantly improved the understanding and application of zinc (Zn) supplementation strategies. Traditional inorganic zinc sources such as zinc sulfate and zinc oxide are still widely used; however, growing concerns regarding bioavailability, environmental pollution, and mineral interactions have led to the development of more efficient and sustainable zinc supplementation approaches. These advances aim to enhance zinc utilization, improve animal performance, and reduce zinc excretion into the environment.

9.1 Organic Zinc Sources

One of the most important advancements in zinc nutrition is the use of organic zinc complexes, including zinc amino acid chelates, zinc proteinate, zinc methionine, and other ligand-bound forms. These organic sources exhibit higher bioavailability compared to inorganic salts due to their stability in the gastrointestinal tract and reduced interaction with dietary antagonists such as phytate. Organic zinc supplementation has been shown to improve growth performance, immune response, reproductive efficiency, and antioxidant status in various animal species while reducing fecal zinc excretion.

9.2 Nano-Zinc Technology

Nanotechnology has introduced a new generation of zinc supplements in the form of nano-zinc oxide (na no-ZnO). Due to its extremely small particle size and increased surface area, nano-zinc demonstrates enhanced absorption and biological activity at lower inclusion rates. Studies have reported improvements in growth performance, feed efficiency, intestinal health, immune response, and antioxidant capacity in animals supplemented with nano-zinc. Additionally, lower supplementation levels may help reduce environmental zinc accumulation. However, further research is required to fully evaluate its long-term safety, optimal dosage, and regulatory aspects.

9.3 Precision Zinc Nutrition

Precision nutrition approaches have emerged as an important advancement in mineral supplementation strategies. These approaches involve formulating diets based on species-specific requirements, physiological status, production stage, and dietary bioavailability. By optimizing zinc inclusion levels and sources, precision nutrition reduces over-supplementation while ensuring adequate zinc supply for optimal performance. This strategy contributes to improved feed efficiency and reduced environmental impact from excess mineral excretion.

9.4 Use of Enzyme Technology

The incorporation of feed enzymes, particularly phytase, has significantly improved zinc bioavailability in plant-based diets. Phytase hydrolyzes phytate complexes that bind zinc in the digestive tract, thereby releasing bound zinc and enhancing its absorption. This allows for lower dietary zinc supplementation without compromising animal performance. Enzyme supplementation also improves overall nutrient digestibility and mineral utilization efficiency.

9.5 Combination and Synergistic Strategies

Recent research has also focused on combined supplementation strategies involving organic zinc, nano-zinc, and other nutrients such as vitamins and amino acids. These synergistic approaches aim to enhance immune function, antioxidant defense, and metabolic efficiency. The integration of zinc with other trace minerals such as copper, manganese, and selenium is also being optimized to maintain mineral balance and prevent antagonistic interactions.

9.6 Environmental Sustainability Considerations

Excessive zinc supplementation has raised concerns regarding environmental contamination due to accumulation in soil through manure application. Recent advances therefore emphasize reducing dietary zinc levels while improving bioavailability through advanced formulations. Organic and nano-zinc sources, along with precision feeding strategies, contribute to lowering zinc excretion without compromising animal productivity. This supports more sustainable livestock production systems.

10. FUTURE DIRECTIONS IN ZINC SUPPLEMENTATION

Future research is expected to focus on improving the safety, efficiency, and cost-effectiveness of novel zinc sources. Areas of interest include controlled-release zinc formulations, nano-encapsulation technologies, and targeted delivery systems that enhance intestinal absorption. Additionally, more studies are needed to determine the long-term effects of nano-zinc and to establish standardized guidelines for its use across different animal species. In recent advances in zinc supplementation have shifted from conventional inorganic sources toward more efficient, bioavailable, and environmentally sustainable alternatives. These innovations play a crucial role in improving animal health, productivity, and sustainability in modern livestock production systems.

11. CONCLUSION

Zinc is an essential trace mineral that plays a fundamental role in animal nutrition, influencing growth, metabolism, immunity, reproduction, antioxidant defense, and overall productivity. Its involvement in numerous enzymatic systems and gene regulation processes makes it indispensable for maintaining optimal physiological functions across all classes of animals, including livestock, poultry, aquaculture species, and companion animals. Adequate dietary zinc is therefore critical for ensuring health, welfare, and efficient production. The bioavailability and utilization of zinc are affected by several dietary, physiological, and environmental factors, including phytate content, mineral interactions, feed composition, and animal health status. Both deficiency and excess of zinc can lead to significant health problems and economic losses, highlighting the importance of maintaining a balanced zinc supply tailored to species-specific requirements and production stages. Recent advancements in zinc nutrition, particularly the development of organic zinc complexes, nano-zinc formulations, and precision feeding strategies, have improved zinc absorption efficiency while reducing environmental contamination from excess mineral excretion. The integration of enzyme technology, especially phytase supplementation, has further enhanced zinc bioavailability in plant-based diets, supporting more sustainable feeding practices.

In conclusion, optimizing zinc nutrition through the use of highly bioavailable sources and scientifically formulated diets is essential for improving animal performance, health, and productivity. Future research should focus on refining supplementation strategies, evaluating the long-term safety of novel zinc sources, and developing sustainable approaches that balance animal requirements with environmental protection. Such efforts will be critical in advancing efficient and sustainable animal production systems.

12. REFERENCES

1. Abd El-Hack, M. E., Alagawany, M., Arif, M., Chaudhry, M. T., Emam, M., & Patra, A. (2019). Organic and inorganic zinc in poultry nutrition: A review. World's Poultry Science Journal, 75(2), 205–217.
2. Alagawany, M., Abd El-Hack, M. E., Patra, A., & Elnesr, S. S. (2021). Zinc supplementation in poultry nutrition: A review on growth, immunity and antioxidant status. Animal Feed Science and Technology, 271, 114726.
3. Bao, Y. M., Choct, M., & Iji, P. A. (2019). Trace mineral nutrition and metabolism in poultry. Animal Nutrition, 5(2), 95–101.
4. Batal, A. B., & Parr, T. M. (2002). Zinc bioavailability in poultry nutrition. Poultry Science, 81(9), 1398–1403.
5. Chand, N., Khan, R. U., & Naz, S. (2020). Zinc nutrition in poultry: Impact on immune response and productivity. Biological Trace Element Research, 195, 1–12.
6. Chasapis, C. T., Loutsidou, A. C., Spiliopoulou, C. A., & Stefanidou, M. E. (2012). Zinc and human health: An update. Archives of Toxicology, 86, 521–534.
7. El-Hack, M. E. A., Alagawany, M., & Mahrose, K. M. (2018). Zinc and immune response in farm animals: A review. Biological Trace Element Research, 186, 1–10.
8. Ghasemi, H. A., et al. (2020). Effect of zinc supplementation on growth and antioxidant status in ruminants. Small Ruminant Research, 184, 106046.
9. Gibson, R. S. (2012). Zinc deficiency and human health. Nutrition Research Reviews, 25(1), 1–14.
10. Hambidge, K. M., & Krebs, N. F. (2007). Zinc deficiency: A special challenge. Journal of Nutrition, 137(4), 1101–1105.

11. Huang, Y., Lu, L., Li, S., Luo, X., & Liu, B. (2020). Organic zinc improves performance and gut health in pigs. Journal of Animal Science, 98(4), skaa054.
12. Jing, M., Wang, X., & Zhao, L. (2019). Zinc bioavailability and metabolism in livestock. Animal Nutrition, 5, 140–146.
13. Khan, R. U., Naz, S., & Dhama, K. (2021). Nano-zinc in poultry nutrition: Growth and immune modulation. Research in Veterinary Science, 136, 1–9.
14. Li, S., Luo, X., & Lu, L. (2019). Effects of dietary zinc sources on growth performance of broilers. Poultry Science, 98(8), 3201–3210.
15. Mavromichalis, I. (2020). Zinc oxide and alternatives in swine nutrition. Animal Feed Science and Technology, 270, 114700.
16. National Research Council (NRC). (1994). Nutrient requirements of poultry (9th rev. ed.). National Academies Press.
17. National Research Council (NRC). (2001). Nutrient requirements of dairy cattle (7th rev. ed.). National Academies Press.
18. National Research Council (NRC). (2012). Nutrient requirements of swine (11th revised ed.). National Academies Press.
19. Naz, S., et al. (2021). Zinc and antioxidant defense in animals: A review. Biological Trace Element Research, 199, 1–14.
20. Patra, A. K., & Lalhriatpuii, M. (2020). Progress in mineral nanoparticles in animal nutrition. Biological Trace Element Research, 197, 233–253.
21. Prasad, A. S. (2013). Discovery of human zinc deficiency and studies in an experimental human model. American Journal of Clinical Nutrition, 98(2), 476–481.
22. Saber, H. S., & Alian, H. A. (2025). Nano zinc supplementation improves broiler performance and carcass traits. Biological Trace Element Research, 204, 909–924.
23. Sahoo, A., Swain, R. K., & Mishra, S. K. (2019). Nano zinc oxide in poultry: A growth and immunity enhancer. Journal of Animal Physiology and Animal Nutrition, 103(5), 1202–1210.
24. Swain, P. S., Rao, S. B. N., Rajendran, D., Dominic, G., & Selvaraju, S. (2016). Nano zinc as an alternative feed supplement. Animal Nutrition, 2(3), 134–141.
25. Suttle, N. F. (2010). Mineral nutrition of livestock (4th ed.). CABI Publishing.
26. Underwood, E. J., & Suttle, N. F. (2001). The mineral nutrition of livestock (3rd ed.). CABI Publishing.
27. Wang, C., & Kim, S. W. (2019). Organic zinc improves immune function and gut health in pigs. Journal of Animal Science, 97, 1–12.
28. Wang, R. L., & Kim, S. W. (2014). Effects of dietary organic zinc supplementation on growth performance and immune responses in animals. Animal Feed Science and Technology, 195, 1–8.
29. Yang, J., Xiong, D., & Long, M. (2025). Zinc oxide nanoparticles in animal nutrition: A review. Nanomaterials, 15(13), 1030.
30. Younas, Z., Mashwani, Z. U. R., Ahmad, I., et al. (2023). Mechanistic approaches of nano-zinc in poultry nutrition. Molecules, 28(3), 1064.
31. Yuan, J., Wang, Y., & Wang, Y. (2011). Effect of zinc on immune function in animals. Biological Trace Element Research, 143, 1546–1557.
32. Zhao, J., Shirley, R. B., Dibner, J. J., Ulanov, A. V., & Whitehead, T. R. (2014). Bioavailability of organic and inorganic zinc sources in animal nutrition. Journal of Animal Science, 92(5), 2075–2082

33. Zhao, J., Shirley, R. B., & Dibner, J. J. (2018). Bioavailability of organic and inorganic zinc in animals. Journal of Animal Science, 96(9), 1–12.