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Role of Nanoparticles as an Alternative Control Strategy Against Avian Coccidiosis: A Comprehensive Review

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ABSTRACT

Avian coccidiosis is one of the most economically important parasitic infections of poultry worldwide, which manifests as intestinal damage, low feed efficiency, reduced growth, and high mortality. Protozoan parasites of the genus Eimeria cause coccidiosis, which is traditionally treated with anticoccidial drugs and vaccinations. However, the development of drug resistance, concerns regarding chemical residues, and constraints of control through vaccines have sparked interest in alternative approaches. Recently, nanotechnology has been considered a promising area with promising approach for disease control using targeted delivery systems, improved bioavailability, immunomodulation, and direct antiparasitic impact. Nanoparticles have been shown to disrupt parasite life cycles, enhance therapeutic efficacy, and aid host immune responses. This review explains the use of nanoparticle-based strategies to manage avian coccidiosis, including the modes of action, nanoparticles employed, experimental research, safety aspects, and future perspectives on the use of nanoparticles in poultry production systems.

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INTRODUCTION

Avian coccidiosis is among the most significant parasitic diseases that affect production across the globe and has remained a significant challenge to both commercial and backyard production systems (Abadula et al. 2022). It is caused by various species of obligatory intracellular protozoan parasites of the genus Eimeria, with a high level of host and tissue specificity (Britez et al. 2023). Sporulated oocysts ingested in contaminated litter, feed, or water infect the intestinal cells of the epithelium and undergo multi-complicated asexual and sexual multiplication (Ahmed 2023). It is a process that leads to different levels of intestinal damage, including mild enteritis and poor absorption of nutrients, as well as severe hemorrhage, diarrhea, dehydration, and death (Kumari et al. 2022). Coccidiosis, besides being a clinical disease issue, is a major unrecognized economic burden because even subclinical infections can severely affect feed conversion and growth rate (Rahmani et al. 2024). International estimates have shown that the losses to coccidiosis, both in prevention and treatment costs, are in the billions of dollars per year; thus, the necessity to use effective and sustainable control measures (Rahmani et al. 2024).

The conventional management of avian coccidiosis involves chemoprophylaxis using anticoccidial medications in feed or drinking water (Ahmad et al. 2023). These are ionophore antibiotics and synthetic chemical anticoccidials that are effective at various developmental stages of the parasite life cycle (Chapman and Rathinam 2022). Although these compounds have been useful over the decades, their extensive and prolonged use has triggered the gradual development of drug-resistant parasites (Shang et al. 2025). Resistance decreases the effectiveness of treatments and forces producers to rotate or combine treatments, thus making them more complex and expensive to manage (Corkley et

al. 2022). Moreover, the development of antimicrobial and chemical additives in animal production is also associated with increasing public and regulatory pressure because of the potential presence of additives in meat and eggs, environmental pollution, and the overall problem of antimicrobial resistance (Kiprotich and Aldrich 2022). Such strains are especially high in antibiotic-free and organic production systems, where the options for control have fewer opportunities and outbreaks may be less manageable (Mak et al. 2022).

Vaccination has become an adjunctive/alternative method to chemotherapy and consists of live, attenuated, or even wild-type oocysts that are used to stimulate protective immunity (Nakhaei et al. 2025). In spite of the fact that vaccines may offer long-lasting and species-specific protection, they also have practical limitations (Bigay et al. 2022). Vaccine production is both expensive and technical, administration is sometimes labor-intensive, and protective immunity takes time to form, thus leaving birds vulnerable during early life stages (Guérin et al. 2024). Furthermore, species-specific immunity is common, meaning that multivalent formulations are necessary to cover the major pathogenic species, and the performance of the vaccine can be influenced by maternal antibodies, management conditions, and co-infections (Ahmadivand et al. 2025). Consequently, vaccination is a common practice in breeder and layer production, although it is not always practical and cost-effective in all broiler production systems (Raphael et al. 2025). These limitations have prompted continued research into new, effective, safe, scalable, and compatible innovative control practices that align with current poultry production objectives (George and George 2023).

Nanotechnology has received increasing attention as a potential instrument for animal health and disease control (Kumar et al. 2023). Nanotechnology is the study and use of materials with sizes or dimensions on the order of nanometers, where specific physical, chemical, and biological characteristics are realized by small size and large surface area (Khan et al. 2022). Nanoparticles can be made using metals, polymers, lipids, and other materials, and their surfaces can be easily altered to enhance stability, targeting, and biological interaction (Abdelkawi et al. 2023). Nanoparticle systems have been developed in biomedical and veterinary sciences to deliver drugs, enhance vaccines, and perform diagnostics, antimicrobial treatment, and antiparasitic therapy (Danchuk et al. 2023). Being small, they can engage closely with biological membranes and pathogens, whereas their adaptable structure allows them to release active compounds at will and enhance bioavailability (Smułek and Kaczorek 2022). These properties make nanoparticles particularly appealing for addressing enteric parasitic diseases, such as coccidiosis, where local intestinal delivery and immune regulation are crucial (Mustafa et al. 2025).

The benefits of using nanoparticles for coccidiosis control are multifactorial (Mustafa et al. 2025). Nanoparticles may also be used to preserve anticoccidial drugs or bioactive natural compounds against degradation in the gastrointestinal tract and to deliver the drug to the site of infection more effectively (Mustafa et al. 2025). This localized administration has the potential to increase efficacy and decrease the dose and side effects (Yang and Zhang 2022). Some nanoparticles, particularly metallic and metal oxides, have inherent antimicrobial and antiparasitic activities by disrupting membranes and causing oxidative stress (Mammari et al. 2022). Moreover, some nanoparticle preparations are immunomodulators or vaccine adjuvants that augment mucosal and systemic immunity (Correa et al. 2022). Reinforcement of intestinal immunity is particularly important in coccidiosis, since local cellular immunity in the gut is essential for the generation of protective responses (Lee et al. 2022). Nanoparticle systems represent a flexible platform because of their integration, direct antiparasitic action, and different immune system stimulation, unlike traditional single-target drugs (Li et al. 2025).

Although such promise exists, the use of nanoparticles in poultry parasitology is a relatively recent area, and numerous scientific and practical questions remain unanswered (Abd El-Ghany et al. 2021). The nanoparticle composition, size, charge, and synthesis method can vary, resulting in variability in biological outcomes and making it difficult to compare across studies (Joudeh and Linke 2022). Safety and toxicity should also be considered, especially in animals that produce food, to ensure that the use of nanoparticles does not cause the emergence of new risks to the welfare of animals, food security, or the environment (Okpala and Korzeniowska 2023). However, an increasing amount of experimental evidence suggests that formulations based on nanoparticles can mitigate the parasite burden, bowel mutilations, and performance defects of coccidial disease (Hamid et al. 2023). These results justify further research on nanotechnology as an alternative or complementary method for controlling coccidiosis (Mustafa et al. 2025). This review aims to explore the different mechanisms of nanoparticles in the control of avian coccidiosis.

Overview of Nanoparticles in Veterinary Medicine

Nanoparticles are designed materials with dimensions of 1–100nm in length, which have dissimilar physicochemical and biological characteristics to those of their bulk equivalents (Joudeh and Linke 2022). On this scale, the materials have a greater surface area, altered electrical charge behavior and reactivity, and greater potential to interact with molecules; thus, they are very useful biomedically and for veterinarians (Prasad et al. 2023). Recently, nanoparticles have been used in veterinary medicine as drug delivery, vaccine, diagnostic imaging, antimicrobial therapy, antiparasitic treatment, and nutritional supplementation vectors (Danchuk et al. 2023). Their small size allows them to cross biological barriers, attach to mucosal surfaces, and interact closely with pathogens and host cells, providing better precision and efficiency in therapeutic interventions (Waheed et al. 2022). This is particularly essential in food-producing animals, where the main priority is treatment efficiency, lower dosing rates, and less risk of residues (Khalifa et al. 2024).

Nanoparticles have been used in the veterinary field as advanced delivery systems, making them one of the most significant contributions in this field (Danchuk et al. 2023). Most traditional veterinary medicines have low solubility, are unstable in the gastrointestinal tract, and

have fast metabolism or uneven tissue distribution (Martinez et al. 2022). These drugs can be encapsulated in nanoparticle carriers that allow controlled and sustained release and prevent early degradation (Bai et al. 2022). This enhances the bioavailability and therapeutic index at the expense of toxicity (Chen et al. 2024). Nanoparticles can be engineered to remain stable in the upper digestive tract and discharge their cargo in the intestine, where most pathogens are present in oral delivery systems (Ejazi et al. 2023). Surface modification also permits nanoparticles to selectively attach to tissues or microbial targets, enhancing the local concentration of a drug and decreasing the systemic exposure to the whole body (Osman et al. 2022). Nanoparticles also play an increasingly important role in veterinary vaccines as antigen carriers and immune adjuvants (Nooraei et al. 2023). Nanoparticle platforms have been found to carry antigens more effectively into antigen-presenting cells and shield them against enzymatic damage when the antigens are conjugated to them (Barchi Jr 2022). This increases recognition of the immune system and the period of antigen exposure, resulting in stronger and longer-lasting immune responses (Aljabali et al. 2023). Mucosal immunization through nanoparticle-based vaccine platforms is of special interest, where the generation of local immunity is imperative for mucosal immunization protection against enteric and respiratory disease-causing agents (Hameed et al. 2022). Moreover, nanoparticle formulations can be programmed to deliver antigens and immunostimulatory molecules together, which determines the type and magnitude of the immune response (Aljabali et al. 2023). In addition to drug and vaccine delivery, some nanoparticles have inherent antimicrobial and antiparasitic properties (Sadiq et al. 2023).

Metal and metal oxide nanoparticles can disrupt microbial membranes, interfere with enzyme systems, and induce oxidative stress in pathogens (Mammari et al. 2022). These inbuilt bioactivities qualify them to work directly, but not as carriers (Petrovic and Barbinta-Patrascu 2023). Nanoparticles also have applications in veterinary practice for the control of bacterial infections, protozoan diseases, ectoparasites, and biofilm formation (Kareem et al. 2022). They have also been tested for wound healing, reproductive medicine, and feed technology (Deng et al. 2022). Nevertheless, in addition to these advantages, one should pay special attention should be paid to safety, biocompatibility, environmental effects, and the possibility of residues (Abdulsalam et al. 2025). With the development of research, nanoparticles will become a part of precision veterinary medicine, providing more focused, effective, and sustainable methods to control diseases, such as avian coccidiosis, which is a parasitic disease (Mustafa et al. 2025).

Types of Nanoparticles Used for Anticoccidial Applications

Different types of nanoparticles have been studied in terms of their role in the management of coccidial infections in poultry, with each providing a set of unique structural, functional, and biological characteristics (Lail et al. 2023). An overview of these types of nanoparticles is that they can be divided into metallic, metal oxide, polymeric, lipid-based, and nano-emulsion systems (Ranjbar et al. 2023). The type of nanoparticle to use is determined by the end use, that is, direct antiparasitic action, drug delivery, vaccine enhancement, or gut health modulation (Sadiq et al. 2023). It is important to learn how these systems differ in order to formulate successful anticoccidial plans and reduce toxicity and improve stability under field conditions (Bharti et al. 2025). Very popular nanoparticles include metallic nanoparticles because they possess good antimicrobial and antiparasitic properties (Bajwa et al. 2022). Silver nanoparticles are especially conspicuous and have proved to be widely active in bacteria, fungi, and protozoa (Zhang et al. 2023). Their success is mostly because of their surface reactivity and that they can produce oxidative stress and membrane damage in target organisms (Das et al. 2025). Silver nanoparticles have demonstrated the ability to inhibit oocyst sporulation and the severity of intestinal lesions in experimental models in anticoccidial studies (Mustafa et al. 2025). Because nanoparticles of gold are more stable and can be functionalized easily, half-baked antimicrobials, they can be useful as a carrier of drugs and antigens (Li et al. 2024a). They can be targeted to be delivered and interact with the immune system because of their predictable surface chemistry (Xue et al. 2024). Zinc oxide and copper oxide are studied as metal oxide nanoparticles that can be utilized in enteric disease control (El-Shenawy et al. 2023). Zinc oxide nanoparticles are of particular concern to poultry since zinc is already known to play a crucial role as a trace mineral in gut integrity and immune capability (Fatima et al. 2024). Zinc oxide in nano form has increased antimicrobial activity and level of interaction with intestinal surfaces (Youn and Choi 2022). These particles can contribute to anticoccidial control directly by modifying parasite viability as well as indirectly through improving gut barrier functionality and antioxidant capacity (Bharti et al. 2025). The same situation can be said about copper oxide nanoparticles that also demonstrate antimicrobial effects but demand more stringent dose control as the safety margins are smaller (Woźniak-Budych et al. 2023). Polymeric nanoparticles constitute one of the significant ones in the delivery of anticoccidial drugs and vaccines (Baron et al. 2022). Biodegradable polymers like chitosan are popular because of their biocompatibility, mucoadhesive properties and their controlled release properties (Mura et al. 2022). Chitosan nanoparticles are natural derivatives of polysaccharides, which makes them especially useful in oral delivery systems because the nanoparticles are absorbed by the intestinal mucosa and increase uptake by immune cells (Li et al. 2022). They are extensively researched as vectors of cocoicidal antigens and phytogenic compounds and enhance stability and immunogenicity (Ayyadurai and Ragavendran 2025).

The applications of synthetic biodegradable polymers also make it possible to precisely tune the degradation rate and release kinetics, which is significant in the case of sustained therapeutic action in the gut (Kuperkar et al. 2024). The lipid-based nanoparticles, such as liposomes and solid lipid particles, are created in order to entrap the water-soluble and fat-soluble molecules in lipid matrices (Kesharwani et al. 2023). These systems are especially

efficient in keeping the sensitive molecules intact against gastric degradation and promote absorption of the molecules across the intestinal membranes (Azman et al. 2022). Lipid nanoparticles are investigated in anticoccidial applications where poorly soluble drugs and bioactive compounds of plant origin with antiparasitic effects are investigated (Nemati et al. 2024). They usually have a structure similar to biological membranes which increases the compatibility and prevents irritation (Wang et al. 2022). Nano-emulsions and nanocomposites are systems that are based on combining oils, surfactants, and active compounds in very small droplet structures that enhance the dispersion and bioactivity (Pandey et al. 2022). These are common in the case of essential oils and botanical extracts that have anticoccidial or gut protective effects (Saeed and Alkheraije 2023). Turning this type of compounds into nano-emulsions enhances stability, surface interactions and absorption and ultimately enhances efficacy over formulations that are traditional (Preeti et al. 2023). Together, these various platforms of nanoparticles offer a variety of technological directions to be used in the development of next-generation anticoccidial interventions in a tailor-made manner (Gao et al. 2024).

Mechanisms of Anticoccidial Action of Nanoparticles

The anticoccidial effects of nanoparticles can be achieved in a variety of interlacing ways which can be directly acting on the parasite, improving the delivery of therapeutic agents, and altering the intestinal and immune homeostasis of the host (Mustafa et al. 2025). Instead of the usual single or two biochemical pathways that conventional anticoccidial drugs affect, nanoparticle systems tend to affect a combination of physical, chemical, and biological interplay (Mustafa et al. 2025). This is one of the reasons why they are believed to be promising tools against drug-resistant parasitic infections (Picot et al. 2022). The cellular and molecular mechanisms underlying the mechanism of action are important in the rational design of formulations and safe use (Mohd Zaid et al. 2023). Direct parasiticidal activity is one of the major mechanisms. Some nanoparticles, including metallic and metal oxide particles, are capable of physically and chemically damaging parasite stages, including oocysts and sporozoites (Bajwa et al. 2022). These particles are highly reactive on their surfaces and are extremely small, so they can adhere to the walls and membranes of parasites and interfere with their structure (Zúñiga-Miranda et al. 2023). They can also induce the development of reactive oxygen species, which oxidize lipids, proteins, and nucleic acids in the cells of parasites (Pawłowska et al. 2023). This oxidative stress may damage metabolic enzymes, membranes, and eventually result in the death or infectivity of the parasites (Motavallihaghi et al. 2022). Interference with sporulation and wall permeability has been reported in the case of coccidial oocysts, and this decreases the number of infective stages in the environment (Zhao et al. 2024). The second key process is the enhanced performance and delivery of anticoccidial agents (Nouri 2022). The solubility, stability, and intestinal residence time of drugs or bioactive plant compounds are better when they are encapsulated with nanoparticles (Klojdová et al. 2023). Nanocarriers ensure that active molecules can reach their target site in an active form by shielding them against early degradation by digestive enzymes and changes in pH (Garbati et al. 2024). The controlled release nature enables constant exposure of parasites to therapeutic concentrations, which could increase the efficacy and reduce the overall amount of doses (Shang et al. 2025). Improved delivery also minimizes changes in the drug level, which is significant in delaying the selection of resistance (Ashique et al. 2023). Such surface-modified nanoparticles can also be used to increase localization to intestinal sites of infection by either muco-adhesion or receptor-mediated interaction (Xu et al. 2022). The other ability of nanoparticles to provide anticoccidial protection is through host immunity regulation (Lail et al. 2023). There are nanoparticle materials that activate innate immune pathways that enhance the activity of macrophages and other antigen-presenting cells within the intestinal mucosa (Liu et al. 2022).

Nanoparticles improve antigen uptake and presentation, resulting in greater cellular immune responses, which are necessary to resist intracellular parasites when used as vaccine carriers (Brito et al. 2023). They can facilitate balanced cytokine reactions and enhance local antibody synthesis, which enhances mucosal defenses (Zhou et al. 2025). Increased immune preparedness causes a decrease in the replication of parasites and the severity of lesions, despite infection (Pawłowska et al. 2023). The support of intestinal barrier integrity and microenvironment balance is another important mechanism (Kong et al. 2024). Some nanoparticles, particularly those that include trace elements or bioactive polymers, enhance gut structure, antioxidant conditions, and tight junction stability (Bamigbade et al. 2025). A healthy intestinal barrier prevents parasite infection and secondary bacterial complications (Shu et al. 2023). Certain nano-files also affect populations of gut microbes, preferring those that are beneficial and competitive with pathogens, and are also involved in immune regulation (Li et al. 2024b). Through this indirect mechanism, nanoparticles contribute to the establishment of less favorable intestinal conditions, which allows less favorable coccidial growth (Mustafa et al. 2025). Collectively, these findings indicate that nanoparticle-based anticoccidial strategies are not restricted to a single mechanism of action but rather involve a complex set of direct antiparasitic, pharmacological, and host-supportive actions (Mustafa et al. 2025). This combination of activity profiles has been the basis for their increased relevance as next-generation coccidiosis control candidates (Ahmad et al. 2023).

Experimental Evidence from In Vitro Studies

In vitro studies have provided initial evidence that nanoparticles have the potential to disrupt coccidial parasites (Mustafa et al. 2025). Laboratory tests have demonstrated that the chosen metallic nanoparticles can decrease the rate of oocyst sporulation and damage the viability of the sporozoites under control (Hegazi et al. 2023). These effects are mostly dose-dependent and associated with oxidative damage and membrane disruption (Pyatha et al. 2022). Nano-formulations and nano-emulsions made of plant products have also been shown to inhibit parasite formation (Lakyat et al. 2024).

Table 1: Role of different nanoparticles against avian coccidiosis and their mechanisms

Sr. No.	Nanoparticle Class	Common Materials	Structural Characteristics	Primary Functional Role	Mechanism of action	Delivery Suitability in Poultry	Limitations	Safety Considerations	References
1.	Metallic Nanoparticles	Silver	Solid metal core at nanoscale with high surface reactivity	Direct bioactive agent	Reduces microbial and protozoal viability; inhibits oocyst sporulation in experimental settings	Feed or water supplementation (experimental)	Dose-sensitive toxicity; stability and aggregation issues	Potential tissue accumulation at high doses; requires strict dose control	(Mustafa et al. 2025)
2.	Metallic Nanoparticles	Gold	Stable inert metal core with modifiable surface	Carrier and immunological platform	Enhances antigen or drug delivery rather than direct antiparasitic action	Oral and injectable carrier systems	Higher production cost; limited intrinsic antiparasitic effect	Generally biocompatible but dose evaluation required	(Chandrakala et al. 2022)
3.	Metal Oxide Nanoparticles	Zinc oxide	Metal oxide crystalline nanoparticles	Antimicrobial and gut-supportive agent	Supports intestinal integrity and shows antimicrobial effects that may reduce parasite impact	Feed additive route	Narrow optimal dose window	Excess dosing linked to gut irritation and oxidative stress	(Joshi et al. 2025)
4.	Metal Oxide Nanoparticles	Copper oxide	Reactive oxide nanoparticles	Antimicrobial agent	Broad antimicrobial action that may indirectly reduce enteric pathogen pressure	Experimental feed inclusion	Higher toxicity risk margin	Requires careful dose regulation	(Ungureanu et al. 2022)
5.	Polymeric Nanoparticles	Chitosan	Biodegradable, mucoadhesive polymer particles	Drug and antigen carrier	Enhances mucosal delivery and immune recognition of anticoccidial antigens	Oral delivery highly suitable	Variable batch properties depending on preparation	Generally favorable safety profile	(Gaglio et al. 2023)
6.	Polymeric Nanoparticles	Biodegradable synthetic polymers (e.g., PLGA-type systems)	Controlled-degradation polymer matrices	Sustained drug release carrier	Protects anticoccidial compounds and enables controlled intestinal release	Oral and parenteral	More complex manufacturing	Biocompatible when properly formulated	(Panditkar et al. 2026)
7.	Lipid-Based Nanoparticles	Liposomes	Phospholipid bilayer vesicles	Encapsulation carrier	Protects drugs and antigens from GI degradation	Oral and injectable	Physical stability challenges	Generally low toxicity	(Mehrdadi 2023)
8.	Lipid-Based Nanoparticles	Solid lipid nanoparticles	Solid lipid core carriers	Sustained release system	Improves stability of poorly soluble anticoccidial compounds	Oral	Formulation complexity	Depends on lipid composition	(Mehrdadi 2023)
	Nanoemulsions	Oil-in-water nanoemulsions	Nanoscale droplet dispersions	Phytochemical delivery	Enhances stability and dispersion of plant-derived anticoccidial compounds	Oral via water/feed	Requires surfactants for stability	Surfactant tolerance must be assessed	(Zuccari and Alfei 2023)
9.	Nanocomposites	Polymer–metal or polymer–plant extract composites	Multi-component nanosystems	Combined delivery and bioactivity	Enables dual function: carrier plus antimicrobial component	Experimental	Standardization difficulty	Depends on components used	(Feng et al. 2025)

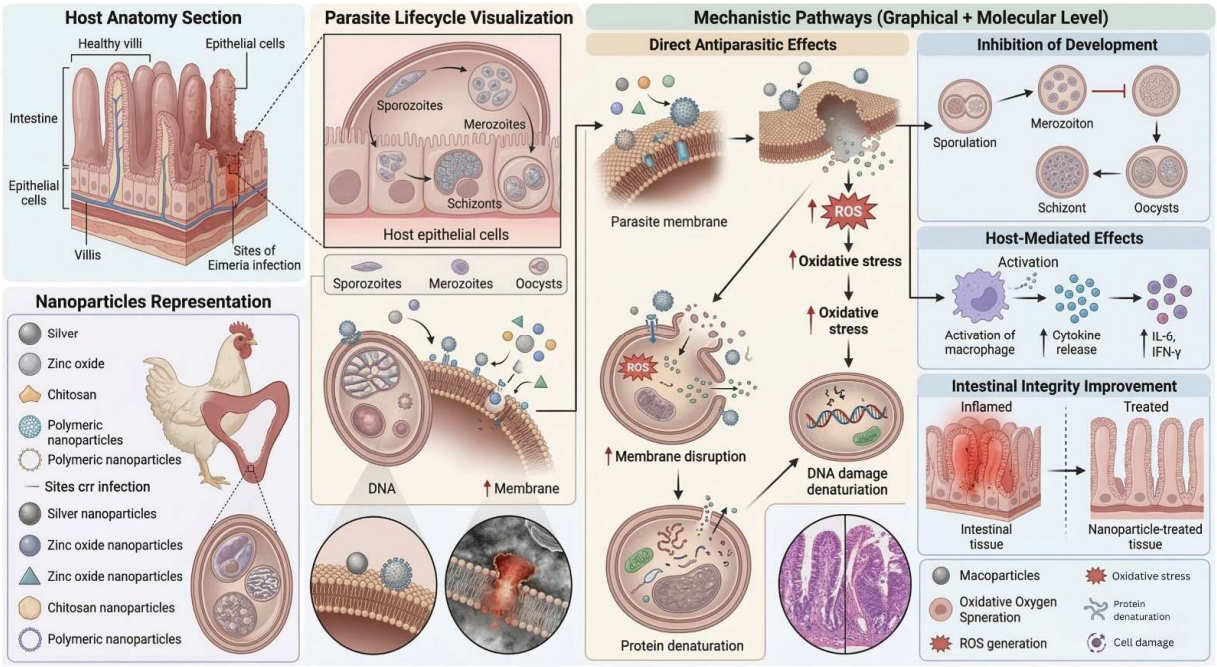

Fig. 1:

The practical applications of bioactive phytochemicals in nanoparticles have been known to enhance the stability and contact efficiency of the bioactive phytochemical with parasite structures, leading to an increase in antiparasitic activity relative to non-nano formulations (Oladipupo et al. 2025). Although the real complexity of the avian intestinal environment cannot be completely recreated in in vitro experiments, the mechanisms acquired through them are supported, and further testing in vivo is directed (Costa et al. 2024).

Evidence from In-vivo poultry studies

Nano-formulated therapeutics or nanoparticle supplementation in experimental coccidial infections have been progressively studied in vivo in poultry (Lail et al. 2023). Metallic nanoparticle trials with controlled doses have demonstrated a reduction in intestinal lesion scores, oocyst shedding, and overall growth performance compared to untreated infected controls (Mustafa et al. 2025). These benefits are frequently associated with decreased intestinal inflammation and increased antioxidant status (Sahoo et al. 2023). The nanoparticle polymer has been explored as a carrier of coccidial antigens in oral vaccine preparations, where it enhances antigen stability and absorption by gut-associated lymphoid tissue, resulting in enhanced immunogenicity and partial protection after challenge (Hashemi et al. 2023). The use of nano-encapsulated herbal extracts and essential oils has also demonstrated potential effects in reducing the burden of parasites and enhancing feed efficiency, presumably because of their joint antiparasitic, antimicrobial, and anti-inflammatory effects (Linh et al. 2022). Although outcomes differ in different studies based on formulation and dosage, the general tendency is that nanoparticle-based strategies have the potential to alleviate the severity of the disease and support the performance of birds (Abbas et al. 2022).

Safety and Toxicological Considerations

Although nanoparticle application to food animals has its benefits, its safety must be considered on its safety (Wasilewska et al. 2023). It is possible that nanoparticles have size-related toxicity and that excessive amounts can damage intestinal tissues, disrupt the balance of gut microbiota, or cause oxidative stress in host cells (Cheng et al. 2023). Nanoparticles of metals are especially concerning because of tissue buildup and possible residues in foodstuffs (Chen et al. 2023). Nanoparticles made of biodegradable polymeric and lipid materials tend to have better safety profiles, whereas the effects of degradation products and their long-term effects are yet to be assessed (Geszke-Moritz and Moritz 2024). Dose-response studies, histopathology, residue examination, and immune and metabolic parameters should be investigated in comprehensive toxicological studies (Chen et al. 2022). Before field usage, safety margins must be defined, and formulations should be optimized to have therapeutic effects with minimal effective doses (Fourie Zirkelbach et al. 2022).

Reality and Conformance Problems.

Nanoparticle technology in commercial poultry production Nanoparticle technology has the following practical issues in translation to the laboratory research (Sadr et al. 2023). There is a need for large-scale, cost-effective synthesis techniques to render nanoformulations economical in terms of feed or water delivery (Hachhach et al. 2025). During storage and mixing with feed ingredients, it must be stable (Waghmare et al. 2022). The delivery system must be strong enough to resist processing and the gastrointestinal environment, as well as release active agents to target spots in the intestines (Chu and Traverso 2022). The regulatory frameworks for nanomaterials in animal production are also changing in most parts, and approval procedures demand

comprehensive information on efficacy, safety, and environmental effects on the environment (Kumari et al. 2023). Nanoparticles must be characterized in a standardized manner in terms of size distribution, surface charge, and composition to be reproducible and comply with regulatory requirements (Sharifi et al. 2022).

Future Perspectives

Future studies on nanoparticle-based control of avian coccidiosis will probably center on multifunctional systems for therapeutic delivery of nanoparticles, immune response generation, and support of gut health (Gao et al. 2024; Ding et al. 2025). Surface functionalization can potentially be advanced with specific binding to parasite stages or intestinal receptors, which should be more specific and have fewer off-target effects (Giltrap et al. 2024; Giraudo et al. 2024). Plant extract-based or biologically found methods of green synthesis could reduce the cost of production and toxicity (Bruno et al. 2022; Tarmizi et al. 2022). Combinations of nanoparticles with vaccines, probiotics, and phytogenic feed additives can have synergistic effects (Hashem et al. 2023; Kamble et al. 2024). The laboratory results should be proven by large-scale field tests in commercial farming processes to learn the true ratio of cost benefits (Dębowski et al. 2022). Better insight into the molecular and cellular interactions between hosts, parasites, and nanoparticles will inform the rational design of next-generation anticoccidial nano-interventions (Shan et al. 2024).

Conclusion

Nanoparticles are among the alternative and complementary approaches to the management of avian coccidiosis because of the growing drug resistance and challenges of escalating restrictions on the use of conventional chemotherapeutics. They have a high ability to deliver specifically, release in a controlled manner, immune-enhancing ability, direct antiparasitic effects, and offer several points of intervention. Their application in reducing parasite load, intestinal damage, and performance losses is supported by experimental evidence from in vitro and in vivo studies. Nevertheless, the application can only be successfully implemented with proper safety analysis, standardization of production, approval from regulators, and economic viability. As interdisciplinary research advances and nanoparticles are further refined, nanoparticle-based solutions can potentially form an integral part of a sustainable program for the management of coccidiosis in production.

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