

Nanobiotechnology in Veterinary Parasitology: Nanoparticle-Based Vaccines and Therapeutics Against Helminths and Protozoa

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Abstract

Parasitic infections caused by helminths and protozoa remain a major constraint to livestock productivity, animal welfare, and public health worldwide, particularly in the face of escalating drug resistance and limited vaccine efficacy. Conventional antiparasitic therapies are increasingly compromised by poor bioavailability, rapid systemic clearance, host toxicity, and environmental contamination. In this context, nanobiotechnology has emerged as a transformative approach in veterinary parasitology, offering innovative solutions for targeted drug delivery, advanced vaccine platforms, and highly sensitive diagnostic tools. This review critically synthesizes recent advances in nanoparticle-based therapeutics and vaccines for the control of major veterinary parasites, including *Leishmania*, *Trypanosoma*, *Eimeria*, *Haemonchus contortus*, and *Fasciola hepatica*. Organic nanocarriers such as polymeric nanoparticles, liposomes, and solid lipid nanoparticles are discussed alongside inorganic and metallic nanoparticles, highlighting their mechanisms of action, pharmacokinetic advantages, and immunomodulatory potential. Particular emphasis is placed on nano-enabled strategies to overcome anthelmintic resistance, enhance intracellular targeting, and induce balanced humoral and cellular immune responses. Additionally, the role of nanotechnology in diagnostics, nutritional supplementation, mycotoxin mitigation, and One Health-oriented disease management is explored. Despite significant promise, challenges related to nanotoxicity, tissue retention, and regulatory harmonization remain critical barriers to field implementation. Overall, this review underscores nanobiotechnology as a pivotal platform for sustainable, precise, and next-generation parasite control in veterinary medicine.

Keywords: Nanobiotechnology; Veterinary parasitology; Nanoparticle-based vaccines; Antiparasitic drug delivery; Helminths; Protozoa; Anthelmintic resistance; One Health

Introduction

The global livestock industry and companion animal health sectors are currently confronting a profound crisis characterized by the diminishing efficacy of traditional antiparasitic agents. Parasitic infections, encompassing a diverse array of helminths and protozoa, remain primary drivers of economic loss, reduced animal welfare, and threats to public health through zoonotic transmission (Buzatti et al., 2020; Sharma et al., 2021). Recent data suggests that the escalation of anthelmintic resistance is now outpacing the development of traditional chemical classes, necessitating a radical shift in pharmacological strategy (Hossain et al., 2025). Conventional veterinary formulations, including powders, tablets, and standardized injections, frequently suffer from significant pharmacological limitations such as poor aqueous solubility, restricted bioavailability, rapid systemic clearance, and an inability to penetrate complex biological barriers or reach intracellular niches (Chen et al., 2015; Soni et al., 2014). These challenges have necessitated the emergence of veterinary nanomedicine, a field that leverages the unique properties of materials at the nanoscale to revolutionize drug delivery, vaccine development, and diagnostic accuracy (Ianiski et al., 2022; Aruna et al., 2023; Gelaye, 2024).

Nanobiotechnology involves the design, synthesis, and application of materials with at least one dimension in the 1 to 1000 nanometer range (Aruna et al., 2023; Gelaye, 2024). At this scale, matter exhibits physicochemical characteristics that differ fundamentally from bulk materials, including an exceptionally high surface area-to-volume ratio, enhanced reactivity, and the capacity for precise surface functionalization (Gelaye, 2024; Stijlemans et al., 2017). These attributes enable nanoparticles to serve as sophisticated delivery vehicles that can protect therapeutic cargos from enzymatic degradation and facilitate the targeted release of drugs directly at the site of infection (Patra et al., 2024). Furthermore, the ability of nano-carriers to bypass physiological barriers, such as the blood-brain barrier (BBB) or the thick intestinal mucosa in ruminants, allows for lower systemic doses and reduced toxicity (Zhu et al., 2025). In the context of "One Health," the integration of nanotechnology into veterinary parasitology is not merely a technical advancement but a strategic necessity to reduce the environmental footprint of chemical therapies and mitigate the rise of multi-drug resistance (MDR) (Ravvaz et al., 2024; Ungogo et al., 2022).

The financial investment in this domain reflects its perceived transformative potential. Global funding for nanotechnology research has surpassed US\$67 billion, with substantial portions dedicated to life sciences and drug delivery (Ianiski et al., 2022). Countries such as Brazil have identified nanotechnology as a priority area for technological innovation, focusing on its application in animal health to reduce residues in the food chain and enhance the productivity of the livestock sector (Aruna et al., 2023; Nemati et al., 2024). Recent initiatives in the South American livestock sector have specifically targeted the use of polymeric nanoparticles to deliver recombinant proteins for long-term parasitic immunity (Silva et al., 2025). By "nano-nizing" existing drugs, researchers can enhance the penetration of the resilient cuticles of nematodes and the cell membranes of intracellular protozoa, thereby extending the utility of the current pharmacopeia while developing novel therapeutic classes (Elikaee et al., 2025; Nemati et al., 2024).

Figure 1.1 The Multi-Faceted Applications of Nanotechnology in Sustainable Animal Health and Production



2. Physicochemical Classification and Structural Properties of Nanocarriers

The selection of appropriate nanomaterials for veterinary applications is dictated by the biological requirements of the target parasite and the physiological environment of the host. Nanocarriers used in parasitology are broadly categorized into organic, inorganic, and complex nanostructures (Kelleci, 2025). This classification is essential because the chemical nature of the carrier determines its degradation rate, cargo capacity, and interaction with the host's immune system.

Organic Nanoparticles: Polymeric and Lipid-Based Systems

Organic nanoparticles have received extensive attention in recent veterinary literature due to their inherent biocompatibility and biodegradability, which are critical for maintaining food safety standards in livestock (Bante et al., 2025). Polymeric nanoparticles, specifically those synthesized from poly (lactic-co-glycolic acid) (PLGA) or chitosan, offer versatile platforms for the encapsulation of both hydrophilic and hydrophobic molecules (Seyed et al., 2025). PLGA is a synthetic polyester favored for its controlled release kinetics and regulatory approval in many medical applications; recent studies highlight its ability to maintain therapeutic drug concentrations for extended periods in the rumen, reducing the frequency of dosing (Jaikishan et al., 2024).

Conversely, chitosan, a natural polysaccharide derived from chitin, is valued for its mucoadhesive properties and its unique ability to stimulate innate immune responses, acting as a natural adjuvant for oral vaccines (Altemimi et al., 2024). By utilizing these polymeric systems, researchers have

successfully bypassed the "first-pass metabolism" that often inactivates traditional anthelmintics (Seyed et al., 2025).

Lipid-based systems, including liposomes and solid lipid nanoparticles (SLNs), are particularly effective for improving the solubility of lipophilic antiparasitic drugs that otherwise show poor absorption. Liposomes are composed of phospholipid bilayers that can encapsulate a wide range of materials, protecting them from premature degradation in the bloodstream (Soni et al., 2014). Solid lipid nanoparticles (SLNs) represent an evolution of this concept, utilizing a solid lipid matrix (such as waxes or triglycerides) to provide higher physical stability and more controlled release profiles compared to traditional emulsions (Nemati et al., 2024). Recent 2025 assessments have demonstrated that SLNs can significantly enhance the bioavailability of plant-derived essential oils when used against intracellular protozoa like *Toxoplasma gondii*, ensuring the cargo reaches the parasite's niche without being degraded by host enzymes (Alshamrani, 2025).

Table 2.1 Comparative Characteristics and Advantages of Organic and Lipid-Based Nanocarriers in Veterinary Parasitology

Nanocarrier Type	Primary Composition	Advantages in Parasitology	Citations
Polymeric NPs	PLGA, Chitosan, PLA	Biodegradability, controlled release, high stability	(Seyed et al., 2025; Bano et al., 2022)
Solid Lipid NPs	Glycerides, waxes	Enhanced bioavailability, drug stability	(Soni et al., 2014; Bano et al., 2022)
Liposomes	Phospholipids	Cell targeting, protection from enzymes	(Chen et al., 2015; Bano et al., 2022)
Nanoemulsions	Submicron oil droplets	Delivery of insoluble essential oils	(U.S. FDA, 2014; Elikae et al., 2025)
Nanocapsules	Polymeric shell, oily core	High payload for hydrophobic drugs	(Nemati et al., 2024; U.S. FDA, 2014)

Nanocapsules and nanospheres differ fundamentally in their structural organization, a factor that dictates their drug-release profiles and interaction with parasitic membranes. Nanocapsules feature a distinct core-shell architecture, typically consisting of a polymeric shell surrounding an oily or aqueous core where the therapeutic agent is dissolved (Petrov et al., 2025). In contrast, nanospheres function as matrix systems where the drug is uniformly dispersed or adsorbed throughout a solid polymeric network (Sharif et al., 2024). These structural differences are critical for "smart" drug delivery; while nanospheres provide a gradual matrix erosion release, nanocapsules are increasingly utilized for high-load lipophilic anthelmintics, protecting them from the harsh acidic environment of the ruminant stomach (Gelaye, 2025).

Further expanding this architectural repertoire are Nanoemulsions, which consist of droplets typically in the range of 20 to 200 nm. These systems provide exceptional stability against sedimentation and creaming due to their small size and Brownian motion (Hossain et al., 2025). In veterinary parasitology, nanoemulsions are considered ideal for transporting water-insoluble substances, such as essential oils or synthetic antiparasitics, across complex mucosal membranes (Altemimi et al., 2024). Recent 2025 studies have demonstrated that these systems can enhance the transdermal delivery of drugs, bypassing the skin barrier in zoonotic disease treatment and providing a non-invasive alternative to traditional injections (Li et al., 2025).

3. Inorganic and Metallic Nanoparticles

Inorganic nanoparticles, including gold (Au), silver (Ag), and zinc oxide (ZnO), are increasingly

explored for their intrinsic antiparasitic properties. These materials often function by generating reactive oxygen species (ROS), which induce catastrophic oxidative stress within the parasite, leading to the denaturation of proteins, lipid peroxidation, and DNA fragmentation (Samiei et al., 2024). Recent 2025 studies have confirmed that metallic ions released from these particles can specifically target the mitochondrial enzymes of helminths, effectively halting their energy metabolism (Al-Difaie & Al-Jubouri, 2025).

Silver nanoparticles, synthesized through "green" methods using plant extracts, have demonstrated potent activity against ectoparasites such as ticks (*Rhipicephalus microplus*). For instance, biosynthesized AgNPs have shown a 90% inhibition rate in larval motility by penetrating the resilient chitinous cuticle (Shahzadi et al., 2025). Metallic nanoparticles also serve as excellent diagnostic and theranostic agents. Gold nanoparticles, for instance, can be functionalized with specific ligands for molecular recognition, allowing them to simultaneously serve as a diagnostic probe and a delivery vehicle (Sharif et al., 2024). Other inorganic structures, such as carbon nanotubes and magnetic nanoparticles, provide enhanced sensitivity in bioimaging, enabling the detection of parasites at ultra-low concentrations in veterinary clinical samples (Gelaye, 2025).

3.1 Nanotherapeutic Strategies Against Protozoal Infections

Protozoal parasites, particularly those that inhabit intracellular environments or sequester in privileged tissues, present significant therapeutic challenges. Nanotechnology offers specialized solutions for targeting these organisms by utilizing "stealth" carriers that evade the host's immune clearance while reaching the parasite's niche (Ambrose et al., 2025).

Figure 3.1 Nano-Enabled Strategies for Targeted Control of Protozoal and Helminthic Pathogens



4. Intracellular Targeting in Leishmaniasis

Leishmania species reside primarily within the phagolysosomes of macrophages, a niche that

protects them from many circulating drugs. Nanoparticles are naturally predisposed to be taken up by the reticuloendothelial system, a phenomenon that can be leveraged for passive targeting (Petrov et al., 2025). Recent trials using mannosylated chitosan nanoparticles have shown a significantly higher affinity for macrophage receptors, delivering drugs directly to the site of infection with minimal systemic side effects (Sudhimon et al., 2024).

Furthermore, the acidic environment of the phagolysosome can be used as a trigger for "stimuli-responsive" nanoparticles to release their cargo, such as Amphotericin B, ensuring lethal concentrations are reached only within the infected cell (Mustafa et al., 2024).

4.1 Trypanosomiasis and the Blood-Brain Barrier

African and American trypanosomiasis (Chagas disease) suffer from a lack of innovative pharmaceutical development. In the chronic stage of African Sleeping Sickness, *Trypanosoma brucei* crosses the blood-brain barrier (BBB), leading to neurological symptoms. Nanotechnological approaches now focus on re-formulating existing drugs like pentamidine into carriers capable of traversing the BBB through receptor-mediated transcytosis (Li et al., 2025).

By increasing circulation time and promoting drug uptake into target neural tissues, nano-delivery systems can achieve therapeutic efficacy at doses up to 10 times lower than conventional therapies, thereby reducing the risk of fatal toxicities associated with traditional trypanocidal agents (Hossain et al., 2025).

5. Coccidiosis and Poultry Health

In the intensive poultry industry, coccidiosis caused by *Eimeria* species remains a dominant threat to global food security and economic sustainability (Rahman et al., 2025). Conventional control relies heavily on ionophores and chemicals, but the rapid escalation of multi-drug resistance (MDR) has rendered many traditional treatments ineffective, prompting an urgent shift toward "green" and nano-enabled alternatives (Mustafa et al., 2024).

Nanotechnology has enabled a paradigm shift in this area through the development of multiepitope vaccines and the targeted delivery of anticoccidials. Recent innovations include the use of pyrazole-modified chitosan-iron nanocomposites, which have demonstrated superior efficacy in reducing oocyst shedding compared to standard amprolium treatments (Ashoor et al., 2025).

Recombinant *Eimeria* proteins, such as surface antigens (SAGs) and calmodulin-domain protein kinases (CDPKs), are increasingly being encapsulated in PLGA nanospheres. These platforms act as "slow-release" depots that protect delicate proteins from gastrointestinal degradation while providing prolonged exposure to the host's immune system (Gelaye, 2025). Current 2025 data indicate that these nanovaccines induce robust humoral and cellular immune responses, characterized by a significant upregulation of CD4⁺ and CD8⁺ T lymphocytes (Iqbal et al., 2025). Consequently, these interventions not only reduce oocyst output but also maintain intestinal integrity, leading to significantly improved weight gain and feed conversion ratios (FCR) in broiler chickens under high-density rearing conditions (Shahzadi et al., 2025).

Table 5.1 Nano-Enabled Therapeutic and Diagnostic Applications for Major Veterinary Protozoal Infections

Target Parasite	Nanomaterial Application	Outcome/Benefit	Citations
<i>Leishmania</i>	Mannosylated Chitosan NPs	Targeted delivery to macrophages; 140x activity	(Soni et al., 2014)
<i>Trypanosoma</i>	Polymeric/Lipid Nanocarriers	Crossing the BBB; reduced systemic toxicity	(Biffi et al., 2019; Ungogo et al., 2022)
<i>Eimeria</i>	PLGA Nanospheres (NSLC vaccine)	Enhanced T-cell response; reduced oocyst output	(Wang et al., 2022)
<i>Babesia</i>	Magnetic/Gold NPs	High-sensitivity diagnostic detection	(Gelaye, 2024; Yalcindag et al., 2024)

The use of gelatin beads to deliver live oocysts as a form of "in-house" vaccination represents another innovative application of nanotechnology in poultry, ensuring that day-old chicks receive a controlled dose of the immunogen (Wang et al., 2022).

6. Advanced Nanoparticulate Vaccines: Mechanisms and Adjuvants

The development of effective vaccines against parasites is notoriously difficult due to their complex life cycles and sophisticated immune evasion strategies. Nanoparticles serve as both antigen delivery vehicles and potent adjuvants, bridging the gap between inactivated and live-attenuated vaccines (Bano et al., 2022).

6.1 Nanoparticles as Adjuvants and Immunostimulants

Nanoparticles smaller than 100 nm are ideally suited for rapid uptake by dendritic cells and subsequent transport to the lymphatic system, where the primary immune response is orchestrated (Manju et al., 2024). By mimicking the size and surface characteristics of viruses, nanovaccines can trigger pattern recognition receptors (PRRs), leading to the maturation of antigen-presenting cells (APCs) and the secretion of pro-inflammatory cytokines that direct the nature of the immune response (Gelaye, 2025).

Unlike traditional adjuvants like alum, which primarily stimulate Th2-mediated humoral responses (antibody production), nanoadjuvants are capable of inducing "balanced" immunity. They activate both MHC class I and class II pathways, triggering both Th1 (cellular) and Th2 responses (Petrov et al., 2025). Recent 2025 studies on *Fasciola hepatica* vaccines have demonstrated that mRNA-lipid nanoparticles (LNPs) can induce rapid innate immune activation, including marked neutrophil expansion and cytotoxic T-cell immunity, which is essential for combating parasites that have traditionally evaded conventional vaccines (Alshamrani, 2025).

6.2 Stability and Controlled Antigen Release

A critical advantage of nanovaccines is their ability to protect biological immunogens from proteolytic and enzymatic degradation, a common failure point for oral or mucosal vaccines (Mustafa et al., 2024). Encapsulation within a polymeric matrix, such as PLGA or chitosan, creates a "depot" effect. This allows for the sustained, slow release of antigens sometimes over several weeks which mimics' repetitive natural exposure and effectively eliminates the need for logistically difficult booster doses in large-scale livestock operations (Iqbal et al., 2025).

To further refine this precision, researchers are now utilizing precision nanovaccines that co-deliver antigens and molecular adjuvants (like CpG oligonucleotides) within a single carrier. This

ensures that the APC receives both the target signal and the necessary "danger" signal simultaneously, significantly increasing the efficiency of the resulting immune memory (Li et al., 2025).

7. Nanobiotechnology in Helminth Control: Overcoming Drug Resistance

Helminth infections, particularly those caused by gastrointestinal nematodes, are increasingly resistant to the current arsenal of anthelmintics, including benzimidazoles, imidazothiazoles, and macrocyclic lactones (Buzatti et al., 2020; Sharma et al., 2021). Nanotechnology offers a two-pronged strategy to combat this resistance: enhancing the delivery of existing drugs and developing novel nano-anthelmintics.

7.1 Restoration of Efficacy for Traditional Drugs

Haemonchus contortus, the "barber's pole worm," is highly resistant to albendazole due to SNPs in the beta-tubulin gene (Sharma et al., 2021; Nemati et al., 2024). "Nano-nizing" albendazole into solid lipid nanoparticles has been shown to increase its potency against *H. contortus* by up to 50 times (Nemati et al., 2024). This enhancement is attributed to improved penetration of the parasite's cuticle and increased drug residence time within the host's gastrointestinal tract (Elikaee et al., 2025; Nemati et al., 2024).

Furthermore, nanotechnology facilitates the use of RNA interference (RNAi) to silence genes associated with drug resistance. Silencing the GCY-12 gene in *H. contortus* eggs has been shown to restore their sensitivity to albendazole, providing a blueprint for combining gene therapy with traditional chemotherapy (Nemati et al., 2024).

7.2 Novel Nano-Anthelmintic Agents and Plant-Derived Nanoformulations

The development of nano-anthelmintics represents a critical intervention in the fight against multi-drug resistant (MDR) helminths. Metallic nanoparticles, specifically Zinc Oxide (ZnO) and Selenium (SeNPs), have shown direct anthelmintic activity by disrupting the antioxidant enzyme systems of the parasite (Samiei et al., 2024). ZnO NPs, in particular, induce catastrophic oxidative stress through the generation of reactive oxygen species (ROS), leading to the paralysis and death of adult worms such as *Haemonchus contortus* and equine strongyles (Shahzadi et al., 2025). Recent 2025 data suggests that these metallic nanoparticles can also inhibit the egg-hatching process of nematodes, providing a dual-action approach that reduces both the immediate worm burden and future pasture contamination (Fantatto et al., 2025).

Complementing these metallic agents are plant-derived nanoformulations, which leverage the synergy between nanotechnology and ethnobotany. The encapsulation of bioactive essential oils, such as those from *Eucalyptus staigeriana*, *Cymbopogon citratus*, or *Azadirachta indica* (neem), into nanoemulsions has been shown to enhance their stability and penetration of the resilient helminth cuticle (Mustafa et al., 2024).

Recent field trials in 2024 and 2025 have demonstrated that these "green" nanoformulations can reduce fecal egg counts in sheep by over 85%, offering an eco-friendly alternative to synthetic chemicals and significantly lowering the chemical residue levels in meat and milk products (Altemimi et al., 2024). Furthermore, the use of carbon-based nanomaterials as carriers for these oils has been explored to provide a slow-release effect, extending the duration of protection in the host's gastrointestinal tract (Hossain et al., 2025).

Table 7.1 Efficacy of Nano-Anthelmintic Formulations in Overcoming Drug Resistance and Enhancing Bioavailability

Helminth Target	Nanomaterial/Drug	Mode of Action	Citation
<i>H. contortus</i>	Albendazole-SLNs	Overcoming beta-tubulin resistance; 50x potency	(Nemati et al., 2024)
<i>H. contortus</i>	ZnO Nanoparticles	ROS generation; cuticle damage; enzyme inhibition	(Nemati et al., 2024)
<i>F. hepatica</i>	Nanopeptides	Targeted peptide delivery (Cuba/Brazil study)	(Elikaee et al., 2025)
<i>Schistosoma</i>	Gold Nanoparticles	Mitigation of infection-induced nephrotoxicity	(Elikaee et al., 2025)
Tapeworms	Praziquantel-SLNs	5.67x increase in bioavailability in dogs	(Soni et al., 2014)

In the case of liver flukes (*Fasciola hepatica*) and blood flukes (*Schistosoma*), preliminary research is exploring the use of nanopeptides and gold nanoparticles to target the parasites and mitigate the damage they cause to host tissues, such as the liver and kidneys (Elikaee et al., 2025).

8. Diagnostic and Biosensing Innovations at the Nanoscale

Early and accurate diagnosis is the cornerstone of effective parasite management. Nanotechnology is driving the development of rapid, sensitive, and field-deployable diagnostic tools that surpass the limitations of traditional microscopy and PCR.

8.1 Nanobiosensors for On-Site Detection

Nanobiosensors utilize nanomaterials to detect parasite-specific antigens, DNA sequences, or metabolic biomarkers (Chen et al., 2015; Elikaee et al., 2025). Lateral flow immunoassays (LFIA) based on gold or silver nanoparticles provide colorimetric results that can be read without specialized equipment, making them ideal for use in remote or resource-limited settings (Gelaye, 2024; Yalcindag et al., 2024). For instance, blue silica nanoparticles (Si NPs) have been used to develop highly sensitive assays for detecting antibodies against zoonotic pathogens in serum samples (Yalcindag et al., 2024).

8.2 Magnetic Isolation and "Omics" Integration

Magnetic nanoparticles allow for the rapid isolation and concentration of parasites or their eggs from complex matrices like feces or blood, significantly increasing the sensitivity of subsequent molecular tests (Gelaye, 2024). Furthermore, the integration of nanotechnology with high-throughput "omics" platforms such as the "Haemabiome" sequencing tool enables the comprehensive identification of pathogen communities and the discovery of new vaccine targets through computational epitope prediction (Yalcindag et al., 2024). These advancements allow for real-time monitoring of animal health and the identification of drug-resistant strains before they spread throughout a herd (Elikaee et al., 2025; Yalcindag et al., 2024).

8.3 Nutritional Synergies and Environmental Safety

The application of nanoparticles in veterinary science extends beyond direct therapy to encompass nutrition and the mitigation of environmental toxins, both of which are critical for maintaining the host's overall resistance to parasitic infection.

8.4 Enhancing Mineral and Vitamin Bioavailability

Mineral nanoparticles, such as Selenium (SeNPs), Zinc (ZnNPs), and Iron (FeNPs), offer superior bioavailability and stability compared to traditional mineral salts, largely due to their high surface-to-volume ratio which enhances intestinal absorption (Altemimi et al., 2024). In poultry and ruminants, these supplements act as potent growth promoters and immunomodulators. Recent 2025 broiler trials showed that a combination of SeNPs and ZnNPs significantly improved body weight gain and feed conversion ratios (FCR) while simultaneously boosting immunoglobulin (IgG and IgM) levels to better withstand parasitic challenges (Fantatto et al., 2025).

SeNPs, in particular, are favored for their ability to increase glutathione peroxidase activity, which improves meat quality and oxidative stability (Mustafa et al., 2024). However, because the therapeutic window for selenium is narrow, inclusion rates must be strictly monitored typically between 0.3–0.5 mg/kg to prevent systemic toxicity and ensure "One Health" safety for human consumers (Mohapatra, 2025).

9. Mycotoxin Adsorption in Feed

The contamination of animal feed with mycotoxins (e.g., aflatoxins) suppresses the immune system and increases the severity of parasitic infections. Nanotechnology has introduced "adsorption–degradation" systems where hybrid nanomaterials not only sequester toxins but also catalyze their breakdown in situ (Al-Difaie & Al-Jubouri, 2025).

Nanocomposites utilizing metal–organic frameworks (MOFs) or magnetic adsorbents have demonstrated a high capacity to neutralize Aflatoxin M1 in the gastrointestinal tract, preventing its transfer into milk and meat (Ambrose et al., 2025). These "smart" adsorbents are more efficient than traditional clays because they locally concentrate toxins near active catalytic sites, accelerating the neutralization process even at low concentrations (Mustafa et al., 2024).

9.1 Mechanisms of Nanotoxicity and Tissue Retention

Nanoparticles can induce oxidative stress and genotoxicity if they accumulate beyond the body's clearance capacity. Metallic oxides like TiO₂ and AgNPs have been shown to elevate ROS levels in hepatic and renal tissues, potentially leading to lipid peroxidation and DNA damage (Sumarokova, 2024). A major 2025 review emphasized that silver residues in meat significantly increase when dietary AgNPs exceed 2.5 mg/kg, raising concerns about the "conversion rate" of these materials into toxic ions during digestion (Mohapatra, 2025).

In food-producing animals, the retention of nanoparticles in edible tissues (meat, milk, eggs) is a major concern. Research must focus on the "conversion rate" of nanomaterials into non-nanoscale forms within the gastrointestinal tract and their eventual elimination from the body. Documented toxicity in reproductive systems and the potential for long-term accumulation necessitate the development of robust safety protocols and species-specific guidelines (Gelaye, 2024; Sharma et al., 2021).

10. The Evolving Regulatory Landscape

The regulation of nanotechnology in veterinary medicine is currently a fragmented landscape with "underdeveloped" guidelines that require further validation and global harmonization (Gelaye, 2024). Regulatory bodies like the FDA and the European Commission are continuously refining their definitions of nanomaterials, moving toward more precise criteria based on particle size distribution and physicochemical properties (Sharma et al., 2021; U.S. FDA, 2014).

Table 10.1 Key Regulatory Considerations and Safety Principles for the Implementation of Nanotechnology in Animal Health

Regulatory Aspect	Key Consideration	Citations
Definition	50% particle size threshold (solid particles only)	(Sharma et al., 2021)
Precautionary Principle	Applied when scientific evidence is uncertain	(Sharma et al., 2021)
Food Safety	Assessment of tissue retention and residual levels	(Gelaye, 2024; U.S. FDA, 2014)
Species Sensitivity	Dosing must account for unique physiology (e.g., ruminants)	(Gelaye, 2024; Kelleci, 2025)

The industry is under increasing pressure to ensure that nano-enabled products do not compromise the safety of the human food chain or lead to environmental persistence (Kelleci, 2025; Sharma et al., 2021). This requires a multidisciplinary collaboration among scientists, engineers, and regulatory agencies to establish clear thresholds for the safe use of nanomaterials in animal health (Gelaye, 2024; Sharma et al., 2021).

10.1 Synthesis and Strategic Outlook

Nanobiotechnology represents a transformative paradigm in veterinary parasitology, offering precise tools to overcome the rising tides of drug resistance and the limitations of traditional vaccination strategies. The high surface-to-volume ratio and tunable surface chemistry of nanoparticles enable the development of "smart" delivery systems that maximize therapeutic efficacy while minimizing systemic toxicity (Kelleci, 2025). From the targeted treatment of intracellular protozoa to the development of multiepitope nanovaccines for poultry, the potential applications of this technology are vast and multifaceted.

However, the path to clinical and commercial realization is fraught with challenges. The complexity of the ruminant stomach, for instance, requires specialized nano-encapsulation techniques to shield sensitive molecules from ruminal fermentation (Kelleci, 2025). Moreover, the potential for tissue accumulation and the long-term ecological impact of nanomaterials must be meticulously investigated. To ensure the sustainable and ethical adoption of nanotechnology, the scientific community must prioritize the development of standardized toxicological assessments and transparent regulatory frameworks that align with the "One Health" mission.

As we move forward, the integration of nanotechnology with "omics" (genomics, proteomics, and metabolomics) and digital health monitoring will lead to a new era of personalized care. Wearable biosensors and AI-driven diagnostic platforms now allow for the real-time detection of parasites at the earliest possible stage (Kumar & Sharma, 2025; Sanjay et al., 2025). By harnessing the power of the very small, veterinary science can solve some of its largest and oldest problems, ensuring the health of animals, the safety of the global food supply, and the stability of the agricultural economy.

Conclusion

Nanobiotechnology is redefining the landscape of veterinary parasitology by addressing long-standing limitations of conventional antiparasitic drugs and vaccines. The ability of nanoparticles to enhance drug solubility, prolong circulation time, penetrate biological barriers, and deliver therapeutic agents directly to parasite niches has demonstrated substantial gains in efficacy while reducing systemic toxicity and dosing frequency. Nano-enabled vaccines further represent a major breakthrough by enabling controlled antigen release, improved antigen presentation, and the

induction of balanced Th1/Th2 immune responses, which are essential for protection against complex parasitic life cycles. Beyond therapeutics and vaccination, nanotechnology has expanded diagnostic capabilities through ultrasensitive biosensors and magnetic separation platforms, enabling early detection and real-time monitoring of parasitic infections. The integration of nanomaterials into animal nutrition and mycotoxin mitigation strategies further strengthens host immunity and resilience, aligning with sustainable livestock production and One Health objectives. Nevertheless, the widespread adoption of nanotechnology in veterinary practice is contingent upon resolving critical challenges related to long-term safety, nanoparticle bioaccumulation, environmental persistence, and regulatory standardization. Future research must prioritize species-specific toxicological assessments, scalable manufacturing processes, and harmonized global regulatory frameworks. With continued interdisciplinary collaboration and responsible innovation, nanobiotechnology holds the potential to revolutionize parasite control, safeguard animal and human health, and ensure the sustainability of global food systems.

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